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Rootstock breeding and associated R&D in the viticulture and wine industry

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Executive Summary

Rootstocks are widely used around the world and some regions in Australia are planted entirely on rootstocks. This demonstrates that their use is not a barrier to commercial vineyard viability.

Grapevine rootstocks have been an essential component of grape growing for over 130 years as rootstocks can impart desirable characteristics for grapevine growth. This review examined Australian and international literature on rootstocks, focusing on key issues including updates on tolerance to phylloxera and nematodes. Other related issues include the performance of major selection traits associated with salinity, low water supply, potassium uptake, vegetative growth, grape and wine quality and the propagation of grafted vines. National and international researchers were consulted and a cross-section of growers and nursery operators were surveyed on their perceptions about rootstocks.

Rootstocks are widely used around the world and some regions in Australia are planted entirely on rootstocks. This demonstrates that their use is not a barrier to commercial vineyard viability. However, winegrape growers in many other Australian regions only considered rootstocks as useful for pest-related problems and could not justify paying the additional cost for grafted vines. In more recent times attitudes have begun to change, with many growers identifying the advantages of rootstocks for non pest-related issues and being prepared to pay the cost for good quality grafted vines. It takes about one extra year to pay back the additional investment in rootstocks without factoring in potential improvements in yield and quality.

Many within the wine industry believe future plantings will include progressive replanting of existing vineyards, rather than planting new green-field sites. Replanting will be driven by the build-up of nematodes, the removal of under-performing blocks, changes to scion varieties and clones, and generational change through improvements in irrigation, trellises and production techniques.

The knowledge of rootstock traits used to select against has substantially increased in some situations. There has been quite a focus on salinity, to the extent of identifying the uptake mechanisms into the plant and the potential to identify genetic markers for chloride exclusion in breeding programs. Similarly, the potassium uptake mechanism has been well characterised. Rapid screening techniques have been developed for sodium, chloride and potassium. Whilst a number of techniques have been used to determine water use efficiency (WUE), the scion plays a major role in the plant response and rapid screening has yet to be developed. Likewise, drought tolerance involves a number of different mechanisms that contribute to survival, and the relative importance of these has yet to be determined or developed into rapid screening techniques.

This review examines six main components of rootstock use, covering aspects of germplasm, nursery production, selection and management, research and development, breeding and information management.

Germplasm and source blocks. The cornerstone of any vineyard is good quality, disease-free vines. Elite rootstock plantings need to be declared true to type and tested for virus and disease and maintained in a healthy state. Multiplication source blocks should be derived from elite plantings. The cutting material supplied to the nursery industry must be of high health status, true to type and verified through an agreed system of quality assurance. An Australian Grapevine Foundation Planting Scheme has been proposed in the past but has not progressed. A cohesive approach across relevant industry bodies to maintaining and providing elite planting material to the industry is essential.

Nursery industry. This is another important component of rootstock use in Australia, with many of those surveyed indicating they place a lot of faith in this sector for providing high quality planting material and as a source of information when selecting rootstocks. Constraints on the nurseries include the provision of potentially diseased cutting material from source blocks, the need to work

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with differing quarantine regulations between Australian states, the inability to supply particular variety/rootstock combinations and issues with incompatibility and graftability that add to the cost of grafted vines. Growers are concerned there are no agreed standards for grafted vines and scion/rootstock combinations are often limited to what works best for the nursery.

Selecting and managing rootstocks in the field. Most growers indicated that local experience with rootstocks would be a prime factor in the selection process, although specific information is quite limited in some regions. Many look for rootstocks with more consistent vigour between the variability of seasons, with vigour management linked to an expectation of more consistent fruit quality. Many indicated they could adequately manage rootstocks but there are some exceptional circumstances that prove difficult to manage.

Research and development aspects. Respondents indicated there were enough rootstock varieties available; however, a more thorough evaluation of each variety was required. This is likely to be a short-term view and confined to individual circumstances. Most surveyed growers identified issues with practically all rootstocks, suggesting ongoing research is required to address these issues. Furthermore, some respondents recognised breeding may be necessary to fill particular gaps in rootstock capabilities. The drought during the 2000s has prompted a strong interest in rootstocks with increased WUE and drought tolerance, but there are no clear guidelines for industry on what rootstock to use that will consistently produce a balanced vine across highly variable seasonal climatic conditions.

Breeding and commercialisation of rootstocks. Many respondents took some interest in the CSIRO breeding program, although many noted the lengthy duration of the evaluation and release of rootstocks. New techniques within the breeding program have resulted in the rapid screening of some traits which can be used for assessing current rootstocks and new hybrids. The CSIRO 'Breeding and Strategy Plan' is based around industry consultation in 2002 and review of the plan would be beneficial to ensure a tight focus is held on breeding objectives. Lessons have been learnt from the initial endeavours to commercialise the release of rootstocks that will expedite the process in the future.

Information and knowledge management. Growers believe there is generally plenty of information available, but consider it is not in the best format for them to access and understand. Given the current market cycle of the industry and limited planting of grafted vines, there is not a high demand for information, so putting effort into developing packages of information and disseminating it may not result in increased adoption of rootstocks at this stage. But industry needs to be ready to respond with targeted information when the need arises. Information on rootstocks should be provided at a steady rate through existing channels and consideration given to testing new forms of presentation to meet the needs of those actively seeking information.

Recommendations. Future investment in rootstocks in Australia for evaluation, breeding and commercialisation should be directed towards the following aspects:

1. maintaining rootstock (and scion) source vines as 'high health status' and ensuring that the status is maintained through to the purchaser of the planting material
2. ensuring relevant field evaluation information is available to assist in the selection of rootstocks for vineyard plantings
3. developing rapid screening techniques to select rootstocks with appropriate characteristics and, where gaps in rootstock performance are identified, undertake introductions or targeted breeding to address those gaps.

1. Background

In the past 15 years, the Australian wine industry has experienced exponential growth in export sales followed by a period of reduced sales. During the growth phase, expectations about the potential of the wine industry were high, which resulted in a planting frenzy placing unprecedented demand on planting material, including rootstocks. This has led to excessive planted area, overproduction of grapes, depressed grape prices, low returns to growers and an exodus of growers from the industry. The current economic conditions restrict growers to short-term decision making, and while some may have longer term plans to replant with rootstocks, many are unable to progress with those plans. In addition, climatic conditions have ranged from an extended drought period to the wettest season on record for many wine regions. This has resulted in many growers reconsidering their vineyard management and their vine selection for future plantings. The industry situation is primed for change but economic conditions are restrictive.

Rootstocks are essential in some regions, primarily where soil pests preclude using ungrafted Vitis vinifera vines. Other regions have anticipated that the risk of getting such pests is low and have, at least initially, planted ungrafted vines. Some growers see rootstocks as a risk avoidance strategy and are interested in using rootstocks for a range of abiotic issues, while still ensuring they have pest resistance. Rootstocks were one of the first long-term biological control strategies and remain very effective. Australia has a low adoption of rootstocks compared to around 70% of vineyards worldwide planted on rootstock. Nevertheless, many growers interviewed for this review indicated they were very interested in rootstocks for future plantings, albeit with some degree of uncertainty about when this might happen. The recent drought period has demonstrated that some rootstocks and ungrafted vines did not tolerate the extended dry period and growers continue to seek vines with less variability in growth and yield between seasons.

The Grape and Wine Research and Development Corporation (GWRDC) commissioned a review of research and development (R&D) issues related to grapevine rootstocks and breeding, along with an assessment of industry attitudes to rootstocks according to the Terms of Reference set out in Appendix A. This review considers developments in grapevine rootstocks since the last comprehensive review (May 1994), in consultation with a cross-section of industry representatives and researchers, both domestically and internationally. The aims of the review were to:

- provide a summary of the current use of rootstocks
- identify major gaps in research and development
- evaluate the relevance and significance of the current CSIRO Plant Industry rootstock breeding program
- identify the most effective future investment for GWRDC in relation to breeding, evaluation and commercialisation of rootstocks in Australia.

In South Australia in 2011, 20.8% of the state's vineyards were planted on rootstock (PGIBSA, pers. comm.). The zones with the highest proportions were Lower Murray (43.1%) and Barossa (23.4%). Coonawarra (3.3%), Clare Valley (4.0%), Adelaide Hills (5.0%) and McLaren Vale (9.9%) had relatively low proportions on rootstock.

2. The use of Rootstocks in Australia and historical drivers

Information on the commercial plantings of grafted vines in Australia is quite variable between states. The Phylloxera and Grape Industry Board of South Australia (PGIBSA) conducts an annual survey of South Australian vineyards to identify the area planted on rootstocks. Irregular surveys of rootstock use are undertaken in the Murray Darling region (Victoria and New South Wales) by Sunrise 21. Other Australian wine regions are not routinely surveyed.

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Rootstock cutting sales from vine improvement associations was routinely published but the reporting has been inconsistent in recent years. The downturn in grapevine plantings since the boom period has resulted in some vine improvement associations struggling to survive and maintain rootstock source areas. Total annual rootstock cutting sales through the major vine improvement associations was around 2.1m units in 1989 and 1990. In 1998 and 1999, 6.0m units were produced and this declined to 2.4m units by 2007 and 2008 (Walker and Clingeleffer, 2009). Due to the long lead time, it is difficult for the vine improvement associations to upscale and downscale source blocks in response to such rapid changes in the demand for rootstock cuttings. These cutting sales have been supplemented by commercial nursery grown cuttings, which currently comprise around 50% of all rootstock cuttings grafted.

Over the past 20 years, the mix of rootstock varieties has also changed markedly. During a five year period (1989–1993), May (1994) collated and reported the rootstock cutting sales through Australian Vine Improvement Association (AVIA) members. That data compared with recent information (Table 1) shows substantial changes in the proportions of each rootstock variety sold. In the early 1990s Ramsey, Schwarzmann and 5BB Kober made up nearly 80% of the sales and by the late 2000s, Ramsey and Schwarzmann sales had markedly declined. In more recent years, 101–14, 140 Ruggeri and 1103 Paulsen have become popular and now make up over 70% of the sales. These trends are also reflected in recent industry commentary on rootstock trends (Arbuckle 2011).

***Table 1**: Cuttings distributed from vine improvement associations by rootstock variety, as a percentage of the total over two five year periods, comparing 1989–93 and 2007–11.*

Rootstock	1989–1993 [1]	2007–2011 [2]
Ramsey	54.3	15.2
Schwarzmann	17.6	2.3
K51–40	5.4	0
K51–32	2.6	*
5BB Kober/5A Teleki	7.0	2.1
140 Ruggeri	1.6	16.2
101–14	1.2	10.2
Dog Ridge	1.2	1.7
SO4	1.9	*
99 Richter	3.2	*
5C Teleki	1.7	1.4
1103 Paulsen	*	43.0
110 Richter	*	6.6
Other	2.3	1.3
Mean number of cuttings per year	2,269,400	2,689,292

[1] May (1994). [2] Production from MIAVIS not included. * Production <1% included in other.

May (1994) considered the lack of information on vineyard rootstock plantings for forward planning by the industry as regrettable, and that a vineyard registration scheme may help with planning. The Vine Industry Nursery Association (VINA) encompasses the majority of nurseries supplying grafted grapevines but do not provide information on aggregated sales to guide industry planning. VINA members also have their own rootstock source blocks and there does not appear to be coordination between VINA and AVIA to rationalise source areas or respond to different industry dynamics. The decline in vineyard plantings after the boom has challenged the ability of rootstock source block owners to carry rootstock varieties in low demand. May (1994) suggested a single repository for rootstocks, particularly those not currently being utilised commercially. Currently, there is no central repository and various individual state and federal repositories have been removed, down-sized or public access denied. AVIA maintain a relatively small number of rootstock varieties for public access.

The major reasons for using rootstocks described by May (1994) still remain but the focus has changed. Earlier on the industry focused on nematode and phylloxera tolerance and relied on parentage to match the general soil and climate conditions. More recently, following the drought, the focus has changed to increased WUE, drought tolerance and salt tolerance, Furthermore, the surplus in grape production has increased the focus on better grape and wine quality. The main reasons for using rootstocks will continue to change over time in response to conditions prevailing in the industry. In California, a cessation of rootstock R&D contributed to the replanting problems after phylloxera biotype B became wide-spread (Whiting 1993). Australia needs to ensure it maintains a capability to respond to changing industry circumstances.

Earlier on the industry focused on nematode and phylloxera tolerance and relied on parentage to match the general soil and climate conditions. More recently, following the drought, the focus has changed to increased WUE, drought tolerance and salt tolerance, Furthermore, the surplus in grape production has increased the focus on better grape and wine quality.

May (1994, p9) lists a number of reasons why ungrafted vines may be preferred over rootstocks. Many of the reasons are still valid but some issues and perceptions have changed:

- The higher cost of grafted vines compared with ungrafted vines remains. When the cost of grafted vines is amortised over the life of the vineyard, the difference is not significant and many growers are now prepared to pay the higher price for good quality planting material.
- The availability of grafted material was an issue during the planting boom (late 1990s–mid 2000s) but during more measured rates of planting, grafted vines should be accessible. Specific scion/rootstock combinations may not always be readily available and additional lead time would be required.
- The lower cost of training ungrafted vines is valid in some instances (potted vines), but some nurseries are producing more advanced (taller) grafted vines to speed up vine establishment.
- The introduction of systemic diseases through grafting is still a potential problem, although the risk is reduced. Nurseries are more aware of the issues and are attempting to manage their operations more assiduously. When cutting sales are high, the income can cover the cost of virus and disease screening of mother vine blocks, but a reduction in revenue, due to less industry planting, limits the ability to adequately test under-used mother blocks.
- The perceived greater longevity of ungrafted vines is a characteristic that has not been adequately assessed. The wine industry is dynamic, with regular changing of varieties, clones and management systems with an expected vineyard lifespan of 25–30 years. For example, in the Sunraysia district in 1979, the top wine varieties were Sultana, Muscat Gordo Blanco and Grenache. Thirty years later in 2009, the top varieties are Chardonnay, Shiraz and Cabernet Sauvignon.
- In some cases, there is uncertainty about the most suitable rootstock for a given site but, in most situations, a range of rootstocks are available that would be appropriate.
- The undesirable effects of enhanced vine vigour have largely been addressed by a better understanding of managing grafted vines.

Since the May review, phylloxera has continued to spread and more virulent nematodes have been detected—these remain important determinants of rootstock use. In addition, the drought period of the 2000s has focused the industry's attention on drought and salinity tolerant rootstocks.

May (1994) made reference to the desirability of calculating the economics of using rootstocks in non-phylloxera situations. The economics of using rootstocks have not been specifically addressed, but much more agronomic data is available to assess the economics of planting rootstocks in a range of situations. These include saline soils, better WUE, drought tolerance, improved grape quality and vineyard reconstruction. As a guide, substituting grafted vines into the economic analysis of a model vineyard (Dakis et al., 2001), without factoring in any change in yield or quality, delayed the break-even period by one year and reduced profitability by 1%. In eastern Washington State, Folwell et al. (2001) modelled payback time and internal rate of return over 20 years for Chardonnay and Merlot, comparing ungrafted and grafted vineyards with no conferred benefit in yield and quality from grafted vines. They determined the payback period was 0.7 years longer and the modified internal rate of return was 1.3% less with rootstocks for both varieties. Factoring in yield and quality benefits to economic models would demonstrate the profitability of using rootstocks. The impact of a phylloxera infestation on a regional basis has been calculated up to $49.2m per region for South Australia, over 10 years after infestation (PGIBSA 2002).

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Australia is a relatively low user of rootstocks, although a greater proportion of grafted vines are being included in new plantings, with around 40% of recent South Australian plantings grafted vines.

The rootstock varieties chosen for planting change with time, making it difficult for the management of source blocks to meet specific demands. This is compounded by the limited availability or removal of various repositories of elite material. While some of the reasons described by May (1994) for growers aversion to rootstocks remain valid, R&D has mitigated many of the perceived preferences towards ungrafted vines. The current issues relating to rootstock choice are covered in the section below.

3. Factors Affecting Current Rootstock Choice

This section (and the next) provides more recent information than provided by May (1994), but does not attempt to be a complete review of the subject. Some topics covered by May (loc. cit.) are not included here because they are not particularly relevant or minimal further information is available.

3.1 Phylloxera

Following the discovery of phylloxera in Australia in 1877, rootstocks were introduced in 1900 as the only means to combat its effects and produce viable vineyards, as occurred in Europe and elsewhere. The continued existence of phylloxera in Australia, and the regular new infestations since 1987, shows that phylloxera susceptibility must be considered in any selection of a rootstock . While new infestations have occurred, efforts to upgrade phylloxera management zones have continued in areas where phylloxera is believed to be absent, but has not been checked (Phylloxera Risk Zone [PRZ]). In recent years a large proportion of the PRZ in Victoria, and one area of Queensland, have been inspected and found free of phylloxera and upgraded to Phylloxera Exclusion Zone (PEZ) status. While this process reduces the risk of spread, many growers want to ensure they have phylloxera resistance in any rootstock they choose to plant. The term 'resistance' used here includes 'tolerance' where phylloxera reproduces on the roots but the vine is not debilitated. Interaction between rootstocks and phylloxera is a complex area and a brief overview is given here.

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The identification of biotypes (biotypes is used here to cover terminology used elsewhere, such as clone, race or strain—see Granett et al., 2001) were not reported in Australia in the review by May (1994). Since then, the understanding of phylloxera biotypes has increased greatly. The existence of different biotypes in North America was speculated in 1870 (Riley, 1872, cited in Granett et al., 2001), and subsequent observations of phylloxera populations damaging some rootstocks, but not others, confirmed the proposition. The early classification of biotypes used differential feeding and reproductive behaviour (King and Rilling, 1985), but the use of techniques assessing insect DNA has enabled phylloxera to be categorised more accurately. The replanting of ARG1 (also called AXR1), commenced in 1983 in California due to the spread of a more virulent biotype of phylloxera. It was estimated to cost the industry $750–$1,250 million (Sullivan 1996) and demonstrates how costly the emergence of a more virulent biotype of phylloxera can be. In Europe, 5C Teleki has been reported to display root galling from an aggressive phylloxera biotype and, in combination with water stress, vines were seen to be suffering in the field (Walker et al., 1998).

Corrie et al. (1998) demonstrated that phylloxera from different sources grew differently on Schwarzmann rootstock, and they subsequently used DNA typing to establish phylloxera biotypes in Australia, some of which were geographically distinct (Corrie et al., 2001). Additional work described up to 83 biotypes. Given no evidence of sexual reproduction has been found in Australia, it is speculated that these biotypes were either brought into Australia or mutations have occurred (Corrie et al., 2002b). Similar results have been documented in Europe where one report identified 103 biotypes, that sexual reproduction was rare (possibly before the introduction to Europe), and migration rates between populations were low (Vorwerk and Forneck, 2006). Some biotypes in Australia live exclusively on the leaves (e.g. G52, G54), some exclusively on the roots (e.g. G1, G4, G39, G51) and others live on both roots and leaves (e.g. G2, G3, G35, G53, G56) (Corrie and Hoffmann, 2004).

Subsequent work in the field found some phylloxera biotypes were only associated with particular rootstocks (Corrie et al., 2002a; Corrie et al., 2003). These differences have been further explored using assays conducted in the laboratory and glasshouse. For example, a phylloxera biotype sourced from the King Valley (now classified as G4) did not feed and reproduce on Schwarzmann in laboratory assays. Corrie et al. (loc. cit.) suggested growers should select rootstocks resistant to the phylloxera biotype present in their vineyard, in order to reduce the population density of the pest and reduce the likelihood of resistance to the rootstock. However, rootstock selection may also be guided by other required attributes. For example, in areas where biotype G4 is present, Schwarzmann would not be suited to any drought conditions, and a drought tolerant rootstock that supports low populations of G4 would perform better.

'Resistant' rootstocks that show some root galling in laboratory studies rarely show above ground damage in the field, unless the vines are particularly stressed. Excised root and dual culture studies tend to overemphasize susceptibility, and in the field rootstocks are capable of surviving with low populations of phylloxera on the roots (Grzegorczyk and Walker, 1998). Glasshouse and excised root bioassay studies showed G1 could establish on Ramsey (Korosi et al., 2007, 2011), but in the field G1 was not observed on Ramsey rootstock (Trethowan and Powell, 2007). The reasons for the different reactions between field and controlled environment studies have yet to be elucidated.

Biotypes also differ in their ability to reproduce and influence vine growth of Vitis vinifera (Forneck et al., 2001; Herbert et al., 2010), with G1 and G4 appearing more virulent than six other biotypes tested in Australia. Field sampling of rootstock trials revealed different phylloxera biotypes appearing in different seasons on some rootstocks and variation in numbers between seasons (Powell, 2006). Phylloxera may also adapt to monoculture rootstocks, as demonstrated in Germany, where phylloxera sourced from 5C Teleki roots reproduced better on 5C Teleki roots than on Cabernet Sauvignon roots (Ritter et al., 2007).

A rootstock bred in Germany, Börner, has been touted as immune to phylloxera. In Australia, phylloxera have been observed feeding on Börner resulting in a rapid hypersensitive-like response and in situ death of crawlers (Kellow et al., 2000). In excised root assays, Börner was noted to support limited phylloxera survival to adulthood and egg production for the G7 and G30 biotypes, but not G1, G4, G19 or G20 (Korosi et al., 2011). In potted vines in a glasshouse, none of the six phylloxera biotypes used were able to colonise Börner roots. Electrical Penetration Graph (EPG) results showed adult insects displayed feeding activity on Börner roots, whereas first instar insects, commonly used to test phylloxera resistance, did not feed (Kingston and Powell, 2006). The EPG technique can give an indication of feeding responses within about eight hours and is currently underutilised. Börner rootstock has grown and yielded well in three phylloxera infested field sites in Victoria; however, phylloxera has been found feeding on the roots. This is consistent with other experiences in Europe where Börner is not immune to phylloxera as it was originally touted (Kevin Powell, pers. comm.). Two field trials in the Clare Valley and Adelaide Hills indicate that vines grafted to Börner have low vigour and yield compared to those on other standard rootstocks, such as 5C Teleki, 110 Richter and SO4 (PGIBSA 2011). A summary of the provisional resistance ratings based on excised root and potted vine assays is shown in Table 2.

Table 2: *Provisional resistance ratings of rootstocks to phylloxera biotypes (from Powell 2009).*

Rootstock	Phylloxera Biotype					
	G1	G4	G7	G19	G20	G30
V. Vinifera	S/S	S/S	S/S	S/S	S/S	S/S
Ramsey	T/T	T/T	T/T	T/T	T/T	T/T
Schwarzmann	R/R	R/R	T/T	T/T	T/T	T/T
Börner	R/R	R/R	T/R	R/R	R/R	T/R
110 Richter	T/T	T/T	T/R	R/R	R/R	T/R
1103 Paulsen	T/T	T/T	R/nd	T/T	R/nd	R/T
140 Ruggeri	T/T	T/T	R/R	R/R	R/nd	R/R
5BB Kober	R/R	R/R	T/T	T/T	T/T	T/T

S=susceptible, T=tolerant, R=resistant, nd=not determined (first letter=excised root assay/second letter=potted vine assay)

phylloxera resistance ratings of rootstocks depend on the biotype of phylloxera used in the tests. This means resistance results from overseas are unlikely to provide a definitive result for phylloxera populations in Australia and further testing needs to occur with Australian biotypes .

The variation in ratings of resistance among rootstocks summarised by May (1994), may be due to different biotypes of phylloxera being used in the testing. Rootstock management and response to drier soil conditions may also influence phylloxera-rootstock interactions (Kevin Powell pers. comm.). Overseas ratings of rootstock resistance must be used with caution, as rootstocks grown in Australia should be assessed against the common biotypes found locally. Research has determined that in genetic populations derived from V. cinerea x V. vinifera, resistance behaves as a single dominant gene (Zhang et al., 2009, cited in Clingeleffer and Smith, 2011). This could lead to molecular markers for resistance.

In summary, phylloxera resistance ratings of rootstocks depend on the biotype of phylloxera used in the tests. This means resistance results from overseas are unlikely to provide a definitive result for phylloxera populations in Australia and further testing needs to occur with Australian biotypes . It is not clear whether phylloxera feeding and damage on excised roots or potted vines translates to potential problems in the field. Some rootstock/biotype combinations allow phylloxera to reproduce without significant impact on grapevine performance. This is not desirable as it may create increased opportunities for phylloxera to spread or allow the rootstock to succumb to other environmental stress. A better way forward is to consider using rootstocks that are immune, or reduce the population of the particular phylloxera biotype, but still have the desirable agronomic characteristics.

3.2 Nematodes

Nematodes have been found widely dispersed in sandy soils but the distribution of species is variable. Many regions in Australia have sandy soils, and any replanting of vineyards will generally be on nematode resistant rootstock as predatory nematodes build up during the life of a vineyard. Prior to replanting, a soil nematode test is desirable to confirm the presence, species and concentration of nematodes. Rootstocks are currently the only viable answer to nematodes; however, the continuous use of the same rootstock may lead to the development of more aggressive biotypes of nematodes . Chemical and many biological controls often do not effectively disperse in the soil to reduce and sustain low populations. The potential negative impact of chemicals on other soil biota is also an issue. Soil amendments in the form of organic composts and manures (Akhtar and Mahmood, 1996), and glucosinolates from brassica crops (Rahman and Somers, 2005), can stimulate predatory and free-living nematodes and reduce the populations of plant parasitic nematodes.

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Nicol et al. (1999) provided an extensive review of nematodes in Australian viticulture, including information on the resistance, tolerance and susceptibility for a wide range of rootstocks. However, resistance or tolerance ratings for nematode rootstock combinations can be different depending on the source of information (Walker, 2009). The variation may be due to the species of nematode being incorrect, the presence of aggressive strains, rootstock mis-identification, the method of classifying resistance and ambient conditions of the study. The rating process needs to be standardised for Australian conditions. Virulent populations of nematodes are more common in California where a number of previously resistant rootstocks (Ramsey, Harmony, Freedom and 1613C) were damaged by virulent nematodes. A breeding program has now produced rootstocks capable of growing in the presence of those virulent nematodes. Furthermore, DNA typing is available to assist with the identification of nematodes to species level, but cannot identify virulent biotypes.

Some rootstocks allow nematodes to reproduce without vines being debilitated; hence they are classed 'tolerant'. However, this may allow virulent nematodes to build up and ultimately have a detrimental effect on the plant. In Australia, virulent populations of root-knot nematode Meloidogyne incognita, and a population of M. arenaria, have been found to be relatively aggressive to Ramsey rootstock (Walker, 1997, Walker and Cox, 2011a). 1103 Paulsen also supports high populations of aggressive biotypes of M. arenaria and M. javanica, along with a less aggressive population of M. javanica (Walker and Cox, 2011a). The rootstocks RS–2 and RS–9, developed at the University of California Davis, have shown high resistance towards three root-knot nematode populations in Australia, including an aggressive population of M. arenaria (Walker and Cox, 2011b). However, these two rootstocks are susceptible to root lesion nematode and possibly ring and citrus nematode. A nematode 'resistant' rootstock is not necessarily resistant to all species or biotypes of nematode, and there is a need for multiple nematode resistance in rootstocks . Resistance to M. incognita has been proposed to be a single dominant gene, but rootstocks resistant to other species of Meloidogyne may well have different genes or alleles associated with the resistance. Resistance to M. javanica McLaren Vale strain appears to be a single dominant gene (Clingeleffer and Smith, 2011).

Resistance to Dagger nematode (Xiphinema index) is a prime focus of breeding overseas due to its association with the spread of fan leaf virus, which has significant consequences for grapevines. In Australia, X. index is thought to be limited to a small area in north eastern Victoria. This area is located within a Phylloxera Infested Zone (PIZ), which is expected to restrict movement out of the PIZ, although it may spread within the zone. Early rootstocks developed in California for resistance to X. index using Muscadinia rotundifolia x V. vinifera (e.g. O39–16) are not particularly resistant to phylloxera or root-knot nematode. Further work is proceeding to produce better rootstocks. Muscadinia rotundifolia is resistant to a wide range of pests and diseases (Olmo, 1986). However, it is difficult to work within breeding programs and progress developing M. rotundifolia hybrids has been slow.

> A nematode 'resistant' rootstock is not necessarily resistant to all species or biotypes of nematode, and there is a need for multiple nematode resistance in rootstocks .

A rapid screening method has been used for screening rootstocks, with a range of nematode races and rootstocks only deemed resistant if no egg masses are observed in the roots (Clingeleffer and Smith, 2011). Vines are classed as tolerant if there is less than one egg mass per gram of dry weight root. Vines with more than one egg mass per gram dry weight of roots are classed susceptible (Table 3). Their studies have shown that 30 of the recognised 69 rootstock varieties in Australia allow reproduction of an aggressive strain of M. javanica in the glasshouse. The more virulent nematodes can only be recognised at this stage by culturing the nematode and inoculating potted plants.

Table 3: *Rootstocks screened with a virulent strain of Meloidogyne javanica from McLaren Vale (selected rootstocks from Clingeleffer and Smith, 2011).*

Resistant	Tolerant	Susceptible
101–14 Mgt	1616 C	1103 Paulsen
140 Ruggeri	'5A Teleki'	1202 C
1613 C	Riparia Gloire	5BB Kober
3306 C	Merbein 6262	Merbein 5489
420 A Mgt	Merbein 5512	SO4
99 Richter		Rupestris du Lot
Dog Ridge		5C Teleki
Fercal		
Freedom		
Harmony		
K51–40		
Ramsey		
Schwarzmann		

Techniques for the rapid screening of rootstocks, using known species and biotypes of nematode, have streamlined the assessment of rootstocks and enabled existing rootstocks to be rapidly assessed. Continued collaboration is required with overseas researchers working on resistance markers to ensure Australia can adopt the markers without duplication of research. There is potential for more aggressive races of nematodes to arise, given experiences in California and Australia's reliance on one predominant rootstock, Ramsey, in sandy soils.

3.3 Incompatibility

Issues associated with perceived incompatibility have not been adequately addressed since the review by May (1994). Nurseries have difficulty with grafting particular combinations of rootstock and scion, and some combinations have failed after one or two years in the field. Incompatibility is believed to be largely associated with the presence of virus or viroids and fungal pathogens. A number of trunk disease-related fungi have been described and isolated from some combinations. The hygiene practices of some nurseries have been questioned (Waite, 2006) and poor sanitation of rootstock and scion material used in grafting can introduce many diseases and viruses into grafted vines (see section 4.6).

In grafting an extensive range of rootstock hybrids, there has been no mention of incompatibilities (Clingeleffer, 2000; Clingeleffer, 2007; Clingeleffer and Smith, 2011). Large differences in the diameter of the rootstock and the scion have been reported but were not associated with any observations of incompatibilities (Clingeleffer and Emmanuelli, 2006). The density of wood above and below the graft union indicated that the rootstock and scion grow at different rates (Clingeleffer and Smith, 2011), but no further use of this relationship was investigated in relation to compatibility.

Graft-scion incompatibility continues to be an issue and understanding needs to be improved. Incompatible combinations can be costly for nurseries and replacing young vines in the field that have declined is expensive. Unfortunately, there is little published definitive information on these issues.

“…there is a wealth of useful information still to be extracted from the Australian rootstock trials”.

Cass et al. (2002)

3.4 Soils

May (1994) lamented the lack of attention to soil in Australia when deciding on a suitable rootstock. Since then, an Australian Soil Classification has been produced which combines many of the features of the previously used Northcote system (Maschmedt et al., 2002). This system was used to determine categories of soils for Australian vineyards in 'Viticulture Volume 1—Resources, 2nd Edition' (Maschmedt, 2004). While addressing many of the issues raised by May (1994), the chapter in the textbook is probably not as readily usable as envisaged. There is still room to provide a stand-alone publication of soils for Australian vineyards, which includes information related to rootstock selection.

An attempt to link rootstock trial results with soil descriptions was made in the GWRDC-funded project CRS 95/1. Rootstock trials were predominantly planted on six groups of soils. Other groups of soils, for which there were no rootstock trials, are normally unsuitable for planting (Cass et al., 2002). The trials included a range of sites with low water availability, but no correlation with rootstock performance was attempted. While rootstock performance data was provided by various collaborators, the data was never thoroughly examined for any relationships with soil physical and chemical properties. Perhaps the complexity of the data was too great for the biometric analyses available at the time, but it would certainly be worth investigating the potential for analysing the data set. An initial attempt to relate rootstocks with soil attributes was provided in Whiting (2004), but a more comprehensive guideline should be produced.

“…there is a wealth of useful information still to be extracted from the Australian rootstock trials”.

Cass et al. (2002)

3.5 Potassium

The issue of high potassium soils in Australia compared with overseas is described by May (1994), and subsequently reviewed by Mpelasoka et al. (2003). Basically, the uptake of potassium, which is exacerbated by some rootstock/scion combinations, increases the pH of the juice and wine, particularly if skins are included in the ferment. If left untreated, the higher pH can lead to poorer quality wines, so most wineries add tartaric acid to adjust the pH down to an acceptable level. This is an added expense to winemaking, but is not deemed a significant issue due to the range of grape juice pH accepted by wineries. There are relative differences between grape rootstocks in the uptake of potassium and the juice pH (Ruhl, 1990a,b). Potassium uptake and translocation may be influenced by vine vigour and canopy shading, which are characteristics of some rootstocks. Root uptake, xylem loading and translocation are steps where rootstocks can have an influence.

Since high potassium has been identified as a characteristic feature of Australian vineyards, there has been some degree of focus on potassium uptake in breeding and selecting rootstocks. Ungrafted rootlings of various rootstocks were shown to differ in their growth, water use and ability to accumulate potassium (Kodur et al., 2010). A screening technique for rootstock breeding programs has been developed using flood tanks with a high potassium solution and measuring petiole potassium in small ungrafted rootstock vines. There was a good correlation between rootstock petiole potassium and results for juice pH of vines grafted to the same rootstock in the field (Clingeleffer and Smith, 2011).

Improved management of Ramsey rootstock has, to some extent, mitigated the high uptake of potassium and high pH in juice. Where the vine vigour of Ramsey is not appropriately controlled (such as wet seasons and soils with high water availability), problems with high juice pH persist; hence, alternative rootstocks are sought. Three low potassium uptake rootstock hybrids have been released by CSIRO and preliminary results show juice pH is lower, but the results are confounded by earlier harvesting of the hybrids at lower sugar concentrations. Some winemakers would prefer not to process red grapes from rootstocks with high potassium uptake, such as Ramsey and Schwarzmann. The challenge for breeding programs is to address the issue from both the grower (yield) and winemaker (quality) perspectives.

Rapid screening techniques are available to select for lower potassium uptake in rootstocks and several rootstocks have been released by CSIRO with low potassium uptake characteristics.

Overall, excess potassium in the juice is recognised by many winemakers as having a negative impact on wine quality, however, few wineries penalise growers based on potassium levels in grapes. Rapid screening techniques are available to select for lower potassium uptake in rootstocks and several rootstocks have been released by CSIRO with low potassium uptake characteristics.

3.6 Salinity

Salinity is another issue which is largely a feature of Australian soils and irrigation water. Vines are able to take up sodium and chloride and transfer them to the grapes. There are international guidelines on levels of sodium and chloride accepted in wine, which can have implications for the trade of wine. There has been a reasonable amount of work on the role of rootstocks on this issue in GWRDC-supported projects since the review of May (1994). The work has looked at the mechanisms of salt uptake, various glasshouse-based methods of assessing uptake, response to salinity in the field, salinity and wine and the breeding of hybrids.

Some rootstocks, grafted with a range of grapevine cultivars, have significantly less petiole and juice concentrations of sodium and chloride under saline soil conditions, or when irrigated with saline water. Rootstocks that generally perform well under saline conditions include Ramsey, 140 Ruggeri, 1103 Paulsen, Fercal and SO4 (Walker et al., 1997; Walker et al., 2002; Walker at al., 2010; Stevens et al., 2011). The high vigour of some rootstocks assists with the tolerance to salinity (Walker et al., 2002).

In one trial, the ability of some rootstocks to exclude salt from the juice diminished over time at one site but not another (Tregeagle et al., 2006). While 140 Ruggeri and 1103 Paulsen grew and yielded well in a saline site, 1103 Paulsen excluded sodium and chloride less (Richards et al., 2010). Shiraz tends to accumulate more chloride than Chardonnay, irrespective of rootstock (Walker et al., 2010). The grape berry skin is a significant repository of chloride and sodium. This means the fermentation of grapes including skins exacerbates sodium and chloride release into the wine (Gong et al., 2010). Juice chloride and sodium concentrations correlate well with wine values across a range of rootstocks.

The distribution of salt within a grapevine suggests salt exclusion is occurring at the cellular level. Reduced loading of chloride into the xylem in the roots, and reduced root-to-shoot transport, were considered the differences between a chloride excluding (140 Ruggeri) and non-excluding (K51–40) rootstock (Tregeagle et al., 2010). Chloride transporters across cell membranes have been identified and there is potential for genetic markers to be developed and used for screening. The transport of sodium into cells is less well elucidated. Further understanding of the mechanisms of salt exclusion may come from studies of wild Vitis genotypes collected from arid and saline areas in North America. These collections contain many genotypes with lower chloride uptake than Ramsey (Heinitz and Walker, 2011). V. cinerea var. helleri (V. berlandieri) may provide a dominant, single and fixed allele for chloride exclusion and genetic markers will be pursued (Fort and Walker, 2011).

A flood tank process has been developed to rapidly screen rootstocks for the ability to exclude chloride (Clingeleffer and Smith, 2011), although further replication of the method is required. Under these conditions, 140 Ruggeri excluded of chloride well, consistent with field trial results. Whilst 1103 Paulsen was considered a good chloride excluder in short-term field trials, there is doubt about its ability to exclude chloride in long-term studies, and this was matched by high chloride uptake in glasshouse studies.

Significant progress has been made towards identifying rootstocks that exclude salt and are more appropriate for longer term salinity problems. The identification of the cellular mechanisms will assist progress towards markers for salt exclusion. Collaboration with researchers at the University of California on their genetic work would also allow for further progression.

Significant progress has been made towards identifying rootstocks that exclude salt and are more appropriate for longer term salinity problems. The identification of the cellular mechanisms will assist progress towards markers for salt exclusion.

3.7 Chlorosis

While chlorosis is an important consideration overseas, it is much less of a problem in Australia. It primarily occurs on soils with an alkaline subsoil (sandy and loamy calcareous soils) when spring seasonal conditions are cold and wet. Improved methods of irrigation and soil management, along with an extended period of drought, have diminished this problem in recent years. If wet soil conditions in spring become more regular, then chlorosis may become an issue in some locations. The low prevalence of this issue does not justify Australian breeding programs for iron chlorosis tolerant rootstocks. Rather, the Australian sector should rely on work from overseas. Part of the field evaluation process could include planting potential new rootstocks on highly alkaline soils to assess their tolerance to lime chlorosis. Fercal, a specifically bred lime tolerant rootstock, has only had limited assessment in Australia.

3.8 Soil acidity

The general recommendation that acid soils be ameliorated by incorporating lime prior to planting (May 1994) still applies. Some variation in the tolerance to low soil pH exists between rootstocks, although few can tolerate very low soil pH. Gravesac is a rootstock that has been selected for acid soils; however, testing in Australia has been limited. In soil of pH 5.0–5.5 (near Lake Erie, New York State, USA) Gravesac had higher pruning weights, higher petiole potassium and phosphorous, and higher yield and berry weight than ungrafted vines across four scion varieties (Bates, 2008). Developing rootstocks for this issue is low priority.

3.9 Water supply

Much greater attention has been paid to this issue since the review of May (1994). A series of drier-than-average seasons (some substantially so) has fostered a number of trials supplying grapevines with reduced amounts of water and monitoring responses. Plants can respond to drought by either dehydration avoidance or by dehydration tolerance through mechanisms such as:

1. reducing transpiration
2. developing extensive root systems
3. improving water conductivity within the plant
4. increasing solutes within the plant to increase the water potential
5. producing more biomass per unit of water.

The geographic origin of V. vinifera from the Mediterranean and Middle East is likely to confer a reasonable amount of drought tolerance, while many American species, traditionally used in rootstock breeding, are found in wetter areas of northern and eastern North America or along stream beds in their native habitat—thus, they have only adapted to short drought periods.

Water use efficiency (WUE) is mainly driven by characteristics of the scion, although interactions between the scion and the rootstock can have an influence. Following is a general discussion on WUE and drought tolerance in grapevines, and the specific role played by the rootstock in these aspects.

The definition of WUE can vary and it is often erroneously interchanged with drought tolerance. Improved WUE can be achieved by various mechanisms relating to increasing the biomass production (photosynthesis, yield) and/or decreasing the water use (transpiration, irrigation)—the latter mechanism being the most common. High WUE is largely a function of reduced water use rather than a net improvement in plant production. Plant water use is commonly regulated by moderated leaf function, reduced leaf area and short growth duration.

WUE can be expressed on a whole crop basis (the ratio of the amount of carbon gained in the plant to the water application, including plant consumption, drainage, runoff and evaporation), a whole plant basis (the ratio of carbon gained to water used by the plant) or on a yield basis (tonnes of crop per ML water applied) (Flexas et al., 2010). Whole plant WUE can be measured instantaneously, which does not account for environmental conditions over time or integrated over a longer term. WUE depends on many processes, such as plant photosynthesis, respiration, leaf area index, leaf angle, canopy structure, stomatal density, hydraulic conductivity and leaf transpiration (and other factors), which makes genetic selection and manipulation difficult. Efforts to improve WUE may not necessarily improve drought tolerance.

WUE depends on complex interactions between environmental factors and physiological mechanisms. Under water stress conditions, maintaining plant survival or productivity will come at a 'cost', such that high WUE may not be the ideal compromise between drought tolerance and economic return (Schultz and Stoll, 2010). Reducing transpiration improves WUE, but results in reduced photosynthesis and yield. Specific targets for genetic manipulation and selection include stomatal physiology, plant respiration, mesophyll conductance to CO2 and the Rubisco enzyme specificity for CO2 (Flexas et al., 2010). However, these relate specifically to aspects of the scion and not the root system. For rootstocks to have an influence, signals from the roots are required to mediate these processes. Of more relevance to rootstocks is the observation that improved WUE can be associated with abscisic acid synthesis and signalling, as well as modified aquaporins.

Transpiration efficiency, expressed as dry matter/water transpired, is negatively related to carbon-isotope discrimination (a measure of photosynthetic efficiency), thus the latter may be a useful technique to assess WUE (Gibberd et al., 2001). However, transpiration efficiency was only closely related to WUE of vines in the field under certain circumstances (Walker, 2004). The variation in transpiration efficiency between grape varieties was greater than the variation between rootstocks with well watered vines, although under reduced irrigation and salinity, greater differences emerged between rootstocks (Walker, 2004). Smith (2004) also found that the differences in transpiration efficiency between scion genotypes were substantially greater than between rootstocks under non-saline and non-water stressed conditions.

Williams (2010) calculated tonnes of crop per megalitre of applied water as a measure of WUE. Values ranged from 15.8 (at 25% irrigation) to 4.4 (at 125% irrigation), and while the high WUE value looks impressive, it was associated with very low yield. Depending on the relative cost of irrigation water and returns for grapes, it may not be economically viable to pursue a particularly high WUE figure.

Grafted Shiraz vines that underwent water deficit in pots had reduced the root growth of Schwarzmann and reduced the shoot growth of vines grafted onto 110 Richter, 140 Ruggeri and Ramsey (Collins and Edwards, pers. comm.). All rootstocks had reduced stomatal conductance and increased instantaneous WUE. This response was associated with increased xylem sap abscisic acid concentration and decreased root hydraulic conductivity. This suggests that canopy size, yield and root-to-shoot ratios may not be the only factors affecting WUE with rootstocks. Any drought tolerant response is likely to be derived from the rootstock and scion combination, and not the rootstock alone.

Various field trials have studied the responses of grafted vines to water deficit. In a field trial at Urrbrae, South Australia, rootstocks had a significant impact on scion gas exchange, water status, canopy growth and yield (Soar et al., 2006). An inverse relationship between relative xylem sap abscisic acid and relative stomatal conductance was also observed. While abscisic acid may be an indicator for water use physiology, the trial proposed using instantaneous leaf gas exchange and leaf water potential to identify drought tolerant vines. Shiraz grafted on 5C Teleki and Ramsey were the least sensitive to water deficit, thus conferring more drought tolerance. Speirs et al. (2010) also demonstrated that the root system provided most of the signal regulating stomatal conductance and, under water deficit conditions, rootstocks produced a greater concentration of abscisic acid (ABA) than own-rooted Shiraz. Loveys (2004) also showed stomatal conductance was inversely correlated with petiolar abscisic acid concentration across a range of rootstocks, confirming the potential for using ABA to distinguish high and low water use rootstocks under water stress in the field.

rootstocks that are regarded as more consistently conferring drought tolerance include Ramsey, 140 Ruggeri, 110 Richter and 1103 Paulsen; whereas poorer drought tolerance are exhibited by Schwarzmann, 420A, K51–40 and 101–14

Further field trials of various scions grafted to rootstocks have demonstrated differences between the scion/rootstock combinations in WUE, carbon assimilation, transpiration rates, leaf loss, vegetative growth and yield potential (Loveys, 2004; Stevens et al., 2008; Stevens et al., 2010; Sommer et al., 2010; Stevens et al., 2011). However, some responses have been inconsistent between trial sites. McCarthy et al. (1997) demonstrated, in a shallow sandy soil in the Barossa Valley, non-uniform yield reductions occurred between grafted rootstocks and own-rooted Shiraz with and without irrigation. Stevens et al. (2008, 2010) showed, in deep well drained soils, no change in relative performance of grafted rootstocks where irrigation was reduced by 30–35%. The latter result implies there is no drought specific adaptation being demonstrated within the range of water deficits applied. Furthermore, a high yielding scion/rootstock combination in well watered conditions will also yield higher under reduced water supply. Vigorous rootstocks appear to confer advantages where there are prolonged water deficits, through their ability to develop roots deeper in the soil (Stevens et al., 2008).

As a general summary, rootstocks that are regarded as more consistently conferring drought tolerance include Ramsey, 140 Ruggeri, 110 Richter and 1103 Paulsen; whereas poorer drought tolerance are exhibited by Schwarzmann, 420A, K51–40 and 101–14.

Within the breeding program conducted by CSIRO Plant Industries, various drought-related attributes are being studied. Assessing crop water use index has shown one of the new CSIRO rootstocks, Merbein 5489, has a higher WUE than 1103 Paulsen (less water use, lower pruning weight and lower yield) (Walker and Clingeleffer, 2009). Ungrafted rootstocks in a nursery situation have been monitored for leaf loss and decrease in vigour under drought conditions, but the ability to confer drought tolerance to grafted scions is yet to be proven (Clingeleffer et al., 2011b). While the ratio of yield to pruning weight (Ravaz index) has been suggested as a surrogate for crop water use index (yield/water transpired), new CSIRO rootstocks with a high Ravaz index were less robust than standard rootstocks under deficit irrigation (Clingeleffer et al., 2011a).

Drought tolerance of rootstocks is foremost in many grape growers' minds given the many recent seasons of below average rainfall. There is no clear screening method for drought tolerance as there are many ways drought tolerance can be generated, and WUE is not a robust indicator of drought tolerance.

Rooting pattern, either through finer roots with greater surface area for water uptake or deeper roots to access water, may provide additional strategies to cope with drought. However, the root architecture of nursery vines across 310 genotypes did not show a consistent association between an overall root architecture rating and a reduction in pruning weight following withholding of irrigation (Clingeleffer and Smith, 2011). The deeper rooting strategy may not always be possible with impenetrable soil layers and the authors concluded that drought tolerance is a complex trait that will require greater investigation. Clingeleffer and Smith (2011) reported several potential attributes for assessing drought tolerance (pruning weight reduction, rooting angles, root thickness, carbon isotope discrimination) on 310 experimental genotypes, but 'standard' rootstocks of known drought tolerance were not included to verify which attributes could be useful indicators of drought tolerance. The difficulty in determining suitable traits for drought tolerance is illustrated by the inconclusive results from over more than 10 years of research (Clingeleffer, 2007; Clingeleffer and Smith, 2011).

Drought tolerance of rootstocks is foremost in many grape growers' minds given the many recent seasons of below average rainfall. There is no clear screening method for drought tolerance as there are many ways drought tolerance can be generated, and WUE is not a robust indicator of drought tolerance. Field trial results have been mixed with moderate to high water deficits in hot 'irrigated' areas, not producing any differentiation between rootstocks compared with full irrigation. Where water deficits have been high in cooler areas and in heavier soils, rootstocks may react differently, such that some appear more drought tolerant than others. Although ABA production has been suggested as a possible marker for responses to water deficit conditions, it remains to be adopted as a standard method. This topic requires much further development and clarification if the breeding and selection of rootstocks are to provide answers.

4. Rootstock Physiology and Propagation-Related Issues

4.1 Root system

Some research projects on rootstocks have included studies of the root system. Different rooting patterns in a sandy loam soils have been described for rootstocks, with 1103 Paulsen and 140 Ruggeri having relatively more roots in the upper 40cm of soil (around 70%) compared with Ramsey and Dog Ridge (around 60% in upper 40cm) and Freedom (50% in upper 40cm) (Walker and Clingeleffer, 2009). In potted vines and some field trials, grafted Ramsey has a lower root-to-shoot ratio than other combinations, implying Ramsey is more efficient at supplying nutrients and water to the scion (Smith, 2004). Root physiology is an aspect that could benefit from more research and should contribute to improved understanding on WUE and drought tolerance.

In Australian soils low in phosphorous, more attention could be paid to the uptake of phosphorous and the uptake of nitrogen to reduce the liberation of nitrous oxide—a greenhouse gas emission consideration.

4.2 Nutrition

Rootstocks can influence the nutrient levels within the grafted plant; hence, influencing grapevine performance. The leaf nitrate-nitrogen at flowering, and the yield of Shiraz grafted onto Schwarzmann and 5C Teleki rootstocks, increased in the season following a post-harvest application of nitrogen, but there was no such response with Ramsey rootstock (Holzapfel and Treeby, 2007). There were also differences in grape juice assimilable free amino-nitrogen in vines grafted to the rootstocks 5A Teleki and Ramsey. Where nitrogen applications were limited to the post-harvest period, the minimum value of assimilable free amino-nitrogen, regarded as necessary to ferment musts through to dryness, was not achieved. The authors suggested the typical uptake/storage model for grapevines was not applicable to Schwarzmann grafted grapevines. This was due to a difference in their seasonal pattern of uptake from the soil and/or a difference in the mobilisation of nitrogen within the vine. Therefore, nitrogen fertilisation may need to be modified for different rootstocks. Differences in nitrogen uptake led to differences in fermentation rate and anthocyanin concentration in the wine, but no significant differences in wine aroma, palate or wine total score (Treeby et al., 1996; Treeby et al., 2000).

The accumulation of whole plant biomass in Cabernet Sauvignon grafted to five rootstocks was highly responsive to increasing nitrogen supply, but the rootstock effect on biomass was less pronounced than the impact of nitrogen supply (Zerihun and Treeby, 2002). Keller et al. (2001a) noted 5BB Kober had significantly higher glutamine, organic nitrogen and total nitrogen in the xylem sap than five other rootstocks, but with nitrate it was only higher than two other rootstocks. They found no interaction between scion and rootstock in contrast to other reports, but cautioned against extrapolating their results to other situations. Early vine growth relies on stored carbohydrate and it is possible rootstocks can have an influence on that, but studies are limited. In Australian soils low in phosphorous, more attention could be paid to the uptake of phosphorous and the uptake of nitrogen to reduce the liberation of nitrous oxide—a greenhouse gas emission consideration.

Growers have questioned whether nutrient standards developed with own-rooted vines apply to grafted vines. In one instance, Stevens et al. (2011a) reported that the petiole standard for sodium (>0.5%) determined by Robinson (1986) was applicable to Colombard grafted to Ramsey rootstock. Keller et al. (2001b) reported no impact of rootstock on inflorescence or bunch stem necrosis, conditions sometimes associated with nutrient imbalances. Any differences in nutrient uptake between grafted rootstocks appear to be manageable, provided the relevant petiole and juice concentrations are monitored and adjusted accordingly.

4.3 Vegetative and reproductive growth

Rootstocks can influence vine growth, but results are often contradictory depending on the conditions and location of the experiment and the scion variety. Differences are more apparent in infertile soils or where vines are under stress. Biomass partitioning between the root, shoot, trunk and fruit of potted vines can be influenced by rootstock. Higher fruit-to-shoot ratios reduced the ability of some rootstocks to ripen the fruit, based on sugar concentration (Smith, 2004). However, there were no differences in total plant biomass; hence, the main influence of rootstock was on partitioning rather than net production of assimilate. The scion had a larger impact on shoot development in young vines than the rootstock, and root development of rootstocks can be strongly impacted by scion type (Tandonnet et al., 2010). Rootstocks also affect the intensity and duration of shoot growth, leaf area, trunk size, pruning weight, bud fertility, yield and phenology, with many cases of interactions between scions and rootstocks being observed (Tandonnet et al., 2010 and references therein). These results could explain the unexpected responses with some scion/rootstock experiments.

While many trials show that rootstocks can impact on growth and reproductive development, it is also apparent that the scion and management practices may have more effect than the rootstock.

In a humid environment, root restriction (approximately 15L) within vine row cover cropping had more impact on reducing vine size, shoot vigour and elements of canopy density than did rootstock (Hatch et al., 2011). Cabernet Sauvignon grapevines grafted to Riparia Gloire produced less growth than grafted 101–14 and 420A. Shiraz grafted to three rootstocks developed by CSIRO Plant Industries had a lower leaf area index during a wet season, compared with grafted Ramsey and 1103 Paulsen rootstocks (Clingeleffer et al., 2011a). Starch and soluble sugar reserves can be influenced by rootstocks (Smith, 2004). For example, Shiraz grafted to Ramsey had high pruning weights but a low root-to-shoot ratio and low carbohydrate reserves, which may have impacted on growth in a subsequent season. Rootstocks also influenced the reproductive development of grafted Shiraz scion under similar light, temperature and nutritional conditions (Smith, 2004). In potted vines, Ramsey increased the bunch number and inflorescence development, while 140 Ruggeri reduced flower numbers and was the lowest yielding rootstock. Zeatin type cytokinin concentrations were different between rootstocks at budburst, but not at fruit set (Smith, 2004).

While many trials show that rootstocks can impact on growth and reproductive development, it is also apparent that the scion and management practices may have more effect than the rootstock. Therefore, it is difficult to extrapolate grafted vine behaviour from that of the ungrafted rootstock, and in any assessment of rootstock behaviour it is necessary to evaluate grafted vines.

4.4 Budburst and bud fruitfulness

Some differences in budburst of up to 11 days were described by Smith (2004) with potted vines of Shiraz grafted on different rootstocks. Budburst date correlated with total vine weight from the preceding winter in year two of the trial, but not year three. In year two, earlier budburst also correlated with higher concentrations of cytokinin in the plant sap. Ramsey rootstock displayed earlier budburst in the potted vines and was also observed in the field in grafted Shiraz, but not with Chardonnay or Cabernet Sauvignon scions (Krstic and Hannah, 2003). Other issues, such as increased salinity, may have more impact on budburst. Thus, it is difficult to ascribe consistent effects of rootstock on budburst when it can also be markedly influenced by scion variety and season.

Vigorous Sultana grafted to Ramsey rootstock has decreased bud fruitfulness, indirectly associated with shading on buds, compared to lower vigour own-rooted Sultana. Reducing the vigour of grafted Ramsey vines through judicious irrigation, and exposing buds to greater amounts of light through re-trellising, improves bud fruitfulness. It appears bud fruitfulness can be greater influenced by cultural and environmental conditions than with rootstock selection.

It appears bud fruitfulness can be greater influenced by cultural and environmental conditions than with rootstock selection.

4.5 Yield and fruit quality

It is difficult to quantify a direct rootstock effect on yield, due to the multiple contributors to yield. In most cases, increased yield is due to increased growth and the ability to retain more buds per vine (e.g. on Ramsey and Dog Ridge). Where soil pests exist, grafted rootstocks out yield ungrafted V. vinifera vines. Where there is abiotic stress alone, rootstocks do not always yield better than ungrafted vines.

The inclusion of some basic grape maturity data has become more common in rootstock trials (e.g. Whiting, 2003). Grape berry composition measurements (sugar, acid, pH, potassium, sodium, chloride, nitrogen, anthocyanins and phenols) were made in a series of trials by Krstic and Hannah (2003) and integrated into an overall assessment of rootstocks for three wine grape cultivars (Shiraz, Chardonnay and Cabernet Sauvignon). As alternatives to Ramsey, the rootstock 101–14 (induces earlier ripening) was one of the best performers for all three cultivars. 1103 Paulsen was well rated for Shiraz and Chardonnay, 116–60 Lider performed well with Chardonnay, and 5C Teleki and 140 Ruggeri performed well with Cabernet Sauvignon. The use of 101–14 as a rootstock under conditions of limited water availability would need to be carefully considered. Earlier ripening and higher colour were attributed to vines grafted to 101–14 in an un-replicated trial planting, compared with Schwarzmann, 5C Teleki and six clones of own-rooted Pinot Noir (Henschke, 2006).

There has been more emphasis on wine composition and sensory assessment since the review of May (1994). Gawel et al. (2000) reported differences in wine composition and spectral measures when Cabernet Sauvignon grapes on different rootstocks were harvested on the one day (in some years there were differences in total soluble solids concentration at harvest). Ramsey and 110 Richter rootstocks produced wines with colour density and phenolics in the lower range and 5C Teleki and Schwarzmann in the higher range. Aroma and flavour intensity were greater with 5C Teleki, Schwarzmann and ungrafted vines, compared with Ramsey and 110 Richter. Clingeleffer et al. (2011a) showed higher colour density and total phenolics in wines from two CSIRO hybrid rootstocks grafted to Shiraz, compared with wines from Ramsey and 1103 Paulsen.

Botrytis infection of grapes can affect wine quality. Keller et al. (2001b) found no significant differences between rootstocks for bunch rot, although severity was correlated with berries per bunch and berry weight. Whiting (2002) found greater proportions of bunch rot on more vigorous rootstocks such as 161–49 and 5BB Kober, associated with larger bunches and greater vine vigour—creating more favourable conditions for disease within the bunch. Rootstocks can influence yield, but higher yielding rootstocks do not always have a negative impact on wine quality, as long as vegetative and reproductive growth of the vine is balanced.

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4.6 Propagation and disease issues

Healthy vine planting material is fundamental to successful grape growing, but in periods of high demand, some growers compromise by using material of uncertain sanitary condition. The boom in plantings during the late 1990s resulted in significant strain on nurseries to meet demand and has exposed issues about the quality of planting material. There have been cases of the failure of vines to establish, young vine decline and longer term poor performance of vines. In California, 36.3% of bench-grafted and rootling rootstocks did not meet the California Department of Food and Agriculture regulations for No. 1 grade grapevines (Weber et al., 1996; Stamp, 2001). No equivalent standards are applied in Australia, nor have rigorous surveys of planting material been conducted. It has been anecdotally reported that a substantial amount of planting material distributed during the planting boom in Australia would not have met the Californian standard.

Nursery practices involving source block management, hot water treatment, hydration, nursery sanitation and cold storage all contribute to the production of high quality planting material (Waite and Morton, 2007). Steps to improve nursery practices have been outlined (Waite, 2006), including ensuring the nursery industry is involved in industry planning, vine propagation practices are improved, good planting material is valued by industry and research and education is ongoing.

A number of trunk diseases, such as black-foot disease (Cylindrocarpon spp.), Petri disease (Phaeomoniella chlamydospora) and bot canker (Botryosphaeria spp.), have been associated with young vine decline (Gramaje and Armengol, 2011; Weckert, 2011). These diseases block the xylem vessels and vines suffer under periods of high water demand. Water stress of vines significantly increased the number of diseased plants nine months after inoculation with Petri disease and planting out (Ferreira et al., 1999). Young vines can be infected before they reach the field and contamination can occur in the mother vines or during the propagation process (Weckert, 2011). Surveys of scion and rootstock mother blocks have detected the presence of the diseases. In rootstock blocks, the diseases are symptomless and latent until the vine is stressed. Liminana et al. (2009) reported the mean necrotic area (typical of esca) in 16-year-old rootstock trunks ranged from 33% in 1103 Paulsen to 71% in 101–14, sampled over 11 rootstocks. These diseases have been isolated from soil and it is suggested rain or irrigation splash can infect pruning wounds. Trunk-related diseases have become more prevalent in California since the replanting of ARG1, which is more resistant to these fungi, with new phylloxera resistant rootstock (Gubler 2003). In some countries, rootstock source vines are trellised so that their shoots are off the ground to avoid potential contamination.

The boom in plantings during the late 1990s resulted in significant strain on nurseries to meet demand and has exposed issues about the quality of planting material. There have been cases of the failure of vines to establish, young vine decline and longer term poor performance of vines.

Nursery operations, such as soaking cuttings in water, disbudding, grafting, callusing and planting in field nurseries, have been associated with spread of these diseases, although often at levels not considered to be pathogenic (Gramaje and Armengol, 2011; Weckert, 2011). Other issues, such as poor graft unions, lifting and trimming of young vine roots, poor cold storage and poor transport conditions, provide opportunities for these diseases to establish. Some chemicals will reduce inoculum levels but do not entirely kill infected tissue within the cuttings. The feasibility of treating pruning cuts on rootstock source vines to prevent the entry of disease or, if infected, to suppress the fungus (e.g. phosphorous acid has been demonstrated to have some activity) need to be investigated.

Hot water treatment is claimed to lower the inoculum level of trunk diseases, but work specifically on Phaeomoniella chlamydospora and Phaeoacremonium inflatipes infused into V. vinifera cuttings found hot water treatment did not reduce the inoculum (Rooney and Gubler, 2001). The climatic source of cutting material may influence responses and biological control has shown promising results. Experiments investigating susceptibility periods at different pruning times has produced inconsistent results; however, research indicates the potential infection period after pruning is quite long—up to several months. There is variation in susceptibility between rootstock cultivars.

A recent report (Weckert, 2011) demonstrated there is an ongoing issue with diseased planting material during a period of relatively low demand, where the focus should be on producing high quality vines. The issue needs urgent attention to ensure that future vineyards are disease-free and will be viable for the long-term.

In one study with Pa chlamydospora (and other root fungal pathogens), 161–49 Couderc was less susceptible than 110 Richter and 140 Ruggeri (Gramaje and Armengol, 2011). While in another study with Pa chlamydospora, 3309 Couderc, 420A, Rupestris du Lot, 110 Richter, 5C Teleki, Schwarzmann and Ramsey were less susceptible than 99 Richter, Freedom, Riparia Gloire, 140 Ruggeri and 1103 Paulsen (Eskalen et al., 2001).

Research in this area has progressed markedly and general guidelines for producing healthy young grafted vines are available. However, there is a need for ongoing investigations into minimising the impacts from these diseases. A recent report (Weckert, 2011) demonstrated there is an ongoing issue with diseased planting material during a period of relatively low demand, where the focus should be on producing high quality vines. The issue needs urgent attention to ensure that future vineyards are disease-free and will be viable for the long-term.

4.7 Virus issues

Leaf roll virus has been largely eliminated from plantings in Australia, although several hotspots in Western Australia and South Australia were recently reported. In Western Australia, it has been found in clones deemed clean in the eastern states (Habili and Randles, 2011). This result is disappointing given earlier work to produce clean planting material. It indicates some degree of laxness in monitoring and preservation of clean source vines, or the virus is being transmitted in another way. Rugose wood associated viruses are responsible for graft failures and vine decline after planting, where it is believed combinations of virus from the scion and rootstock induce the stem pitting and grooving symptoms (Bonfiglioli et al., 1998). The change from ARG1 to other rootstocks in California exposed substantially more virus issues, as ARG1 was a symptomless carrier of many viruses. Monitoring for virus content needs regular consideration in Australia as rootstock cultivars change with time (NVHSC and GWRDC, 2002). Rapid PCR testing methods are available, and regular testing is required to ensure the germplam and mother blocks of scion and rootstock varieties remain free of virus.

4.8 Germplasm, industry source blocks and provision of rootstock information

Issues related to germplasm collections were addressed at a workshop in 2002 (NVHSC and GWRDC, 2002). The first resolution in the report requested the National Vine Health Steering Committee (NVHSC) (at the time) to establish a Vine Improvement Reference Group to develop standards for certified planting material to the industry. This is still being addressed under the Australian Grapevine Standards Scheme project. The New Zealand Winegrowers body has already developed standards for certified grafted planting material in New Zealand (New Zealand Grapegrowers, 2011). The second resolution was for the NVHSC to facilitate the development of a national nuclear collection of high health status that would be the foundation of state and regional vine improvement schemes. This resource would need to be supported through boom and bust times and GWRDC indicated its funding support at the time if there was broad industry support. Issues between vine improvement groups at the time have precluded the establishment of a national high health facility with support of all groups.

Constable and Drew (2004) produced a comprehensive review of the health parameters and capabilities for vine improvement groups and accredited nurseries, involving extensive consultation across the industry. A number of recommendations were proposed based on an Australian Grapevine Foundation Planting Scheme to ensure planting material of the required health status and provenance was available to meet the grape and vine nursery needs. Many of the recommendations are yet to be implemented.

The Vine Industry Nursery Association (VINA) represents the interests of leading nurseries in the industry, and has an established accreditation scheme where nurseries follow quality assurance protocols established by VINA, which are audited annually

The Vine Industry Nursery Association (VINA) represents the interests of leading nurseries in the industry, and has an established accreditation scheme where nurseries follow quality assurance protocols established by VINA, which are audited annually. This scheme is further being strengthened by the development of the Australian Grapevine Standards Scheme, to improve variety identification protocols and establish an Australian grapevine standard based around sound propagules for industry.

Several major sources of information have been produced since the review of May (1994), including a revised chapter in a major textbook (Whiting, 2004); a revised publication on rootstock use in South Australia (Dry 2007); the Yalumba Nursery website (www.yalumbanursery.com) and several project reports relating to rootstocks on the GWRDC website (www.gwrdc.com.au). Another example of information sharing is the review of rootstock performance by the Alpine Valleys region in Victoria some 10–15 years after they first started using rootstocks (Wigg, 2006)—it is suggested this exercise could be conducted in other regions.

5. International Situation

The current situation with rootstock breeding, evaluation and commercialisation in a cross-section of other countries was reviewed and a summary is presented here. Most of the rootstocks in use today were developed in the late 1800s and early 1900s by European breeders in response to phylloxera spreading throughout Europe. Much of the early breeding in North America focused on direct producers, bred from local vine species that produced crops and tolerated the local conditions (primarily the harsh winters and phylloxera). It did not focus on rootstocks since Vitis vinifera cultivars were not widely planted, apart from the west coast of USA and New York State. There have been relatively few recently released rootstocks that have gained the popularity of those earlier releases.

5.1 Geisenheim Research Centre, Germany (Dr Ernst Ruhl, pers. comm.; Geisenheim website)

The Geisenheim rootstock breeding program aims for complete resistance to leaf and root galling phylloxera, combined with high affinity between the rootstock and scion, good adaptation to different soil types (particularly high lime content and drought tolerance) and positive effects on grape quality. The majority of the rootstocks used in Germany are crosses of V. cinerea var. helleri x V. riparia, with SO4 being widely used. However, recent warmer and drier summers have moved attention to more drought tolerant rootstocks in the V. cinerea var. helleri x V. rupestris group. Börner is a V. riparia x V. cinerea cross with a high level of resistance to phylloxera but low tolerance of lime ($CaCO_3$), and is one of the more recent releases in Germany. V. cinerea, along with Rici and Cina, has been used extensively in breeding over the last 20 years because of its high phylloxera resistance. The preference in Germany is to have 20 years' experience with new hybrids, including evaluation on grower properties, before official release and the expectation of industry taking them into the commercialisation phase.

The research station at Geisenheim also supervises bud wood production from 160-ha of rootstock mother blocks. Researchers continue to collect and evaluate native American Vitis species, with one project focusing on V. cinerea var. helleri for improving lime tolerance. Biotypes of phylloxera are less of a focus, but secondary pathogens associated with phylloxera damage, particularly Roesleria subterranean (grape root rot), is viewed as an emerging issue. There is also quite a focus on rooting, grafting and wood production, to ensure the material has good nursery characteristics (Dry, 2005). This includes re-selecting within rootstock cultivars for clones of rootstocks. Nurseries need to be registered to propagate and distribute material and must use certified material. Most growers rely on the nurseries for rootstock selection.

Only three rootstocks have been registered and released in France in the last 45 years—viz. Gravesac (1967), Fercal (1978) and Nemadex Alain Bouquet (2010).

5.2 Institut National de la Researche Agronomique (INRA), France (Dr Nathalie Ollat pers. comm. ; INRA website)

Around 10 rootstocks cover 90% of the wine industry in France, with rootstock SO4 widely planted and viewed as a 'safe choice' (much like the initial use of Schwarzmann in cooler areas of Australia), but it does not overcome all the issues. The breeding programs in France were stagnant in the 1990s (Dry 2005), but have since been revived to address grapevine fanleaf virus and the vector nematode Xiphinema index using Muscadinia rotundifolia in breeding programs. Lime tolerance, low vigour, phylloxera resistance, high fertility (fruitset), drought tolerance and grape and wine quality are also important issues to be addressed. The future direction of the program is to develop molecular assisted selection for biotic stress. However, breeding V. vinifera varieties for disease resistance has higher priority with industry and government than rootstock breeding. Transgenic rootstocks produced to resist X. index and fanleaf virus were produced and planted in a trial plot for evaluation, but was destroyed by vandals in 2010. The process for developing and planting out the trial vines involved considerable community consultation, and cost taxpayers €1m.

Only three rootstocks have been registered and released in France in the last 45 years—viz. Gravesac (1967), Fercal (1978) and Nemadex Alain Bouquet (2010). INRA are also interested in evaluating rootstocks from other countries, primarily for drought tolerance. INRA seek a minimum of 10 years for evaluation after selections are made, with the recently released Nemadex Alain Bouquet being bred in 1987 (20+ year process). The Etablissement National Technique pour l'Amelioration de la Viticulture (ENTAV) is a non-government organisation responsible for the conservation and sanitary status of vine material and the distribution of base material to nurseries. INRA release all their material through ENTAV for commercialisation, and like to track the performance of their releases in commercial plantings to learn more about rootstock performance.

5.3 University of California Davis (UCD), USA (Dr Andy Walker; UCD website)

Part of the breeding program in California has focussed on nematode resistant rootstocks for the sandy soils of the Central Valley. Following the development of Ramsey and Dog Ridge, the rootstocks Freedom, Harmony and O39–16 were produced. In other USA wine regions, traditional European rootstocks assessed although ARG1 appeared best suited. The failure of ARG1 in the 1980s and 1990s necessitated a return to European-bred rootstocks, and the popular rootstocks currently are Freedom, 1103 Paulsen and 101–14. Rootstock preference may change in the future as more vineyard replanting is expected than new plantings. Industry recognised there were gaps in the performance of current rootstocks, but was unwilling or unable to fund the expanding breeding programs in the past. The University of California Davis (UCD) are developing rootstocks with more manageable vigour, broader nematode resistance, salt and drought tolerance, virus and Pierce's Disease tolerance and fungal resistance. Although the USA economy is down and there is a reduced demand for rootstocks, the wine industry views the breeding programs as high priority and the current breeding programs are well supported.

One of the major projects involves breeding for, and identifying, the genes conferring resistance to Xiphinema index nematode. Markers that can expedite the screening of hybrid rootstocks have been identified. Seeds supplied as M. rotundifolia x V. rupestris by Prof. H P Olmo actually turned out to be a mixture of unintended outcrosses, and it was discovered that V. arizonica and its hybrids with V. candicans had high resistance to Pierce's disease and dagger nematode. The pathway to release began in 1993–4 when 75 crosses were made, resulting in 5,000 seedlings. In 1996, 1,000 of those were tested for rooting ability and the best 100 were selected for nematode testing. Several stages of nematode testing reduced the number to 33 then 14, and finally five hybrids (listed as UCD GRN 1 to 5; GRN = Grape Rootstock for Nematode) were released in 2008 to University of California licensed nurseries for further field testing (Walker and Ferris, 2009).

UCD have used rapid screening systems for a number of key issues to be addressed. For example, salinity tolerance was examined by testing hybrids of tolerant and sensitive species to determine the genetics associated with sodium and chloride exclusion and to identify the potential markers. Using these techniques, UCD have sped up the basic evaluation process enabling progression to field evaluation sooner. The commercialisation process occurs through the Foundation Plant Services, with most of the promotion of the new rootstocks done by Dr Walker.

5.4 United States Department of Agriculture (USDA), Geneva USA (Dr Peter Cousins)

The focus is on root-knot nematodes (Meloidogyne spp), particularly with the emergence of aggressive populations that feed on and damage previously well regarded nematode resistant rootstocks (e.g. Harmony and Freedom).

The United States Department of Agriculture (USDA) work is conducted collaboratively with a number of other groups in the USA. The focus is on root-knot nematodes (Meloidogyne spp), particularly with the emergence of aggressive populations that feed on and damage previously well regarded nematode resistant rootstocks (e.g. Harmony and Freedom). USDA have developed methods for the rapid screening of germinated seedlings inoculated with nematodes, and are able to screen over 5,000 seedlings in one season. Around 1% of seedlings show resistance to aggressive root-knot nematodes, and material from promising selections are bulked up and made available to industry for further evaluation. Three improved nematode resistant rootstocks bred in 2000 (Matador, Minotaur and Kingfisher) were released in 2010 and a further 20 rootstock hybrids have been grafted and planted in 2010 for field evaluation.

The work has also characterised additional sources of resistance above that found in V. champinii rootstocks, and that these new sources of resistance offer protection against a broader range of nematodes. They have been unable to develop molecular markers associated with resistance to root-knot nematode. An evaluation of rootstocks in southern Texas, where Pierce's disease is prevalent, revealed that Dog Ridge rootstock showed fewer disease symptoms and greater pruning weights than four other rootstocks. In north Florida, Ramsey had the highest survival against Pierce's disease (Lu et al., 2008). There is an extensive fraternity of grape breeders across North America who share information and vine material, but most of the focus is on fruiting varieties, not rootstocks (see www.ibiblio.org/grapebreeders).

5.5 Washington State University, USA (Markus Keller; WSU Prosser website)

The grape industry in Washington State has very few issues that require rootstocks, apart from some lime chlorosis in high pH soils and, consequently, more than 99% of the grapes are ungrafted. There are some rootstock evaluation trials in place, in the event of further phylloxera infestations or if nematode populations increase. This work includes monitoring growth, yield and its components, fruit composition and wine quality. In one trial at Prosser, in the absence of phylloxera or nematodes, results were primarily influenced by annual climate, spatial differences across the vineyard and the scion varieties. The rootstocks induced few and often minor differences in performance and scion varieties modified the rootstock impact. Rootstock evaluation has a low priority and no breeding is undertaken; however, the high health status of source material is maintained for industry use, even though current demand for rootstocks is low.

5.6 Marlborough Wine Research Centre, Blenheim, New Zealand (Dr Mike Trought)

Phylloxera spread throughout New Zealand over a period of about 30 years and growers rely on the traditional suite of European rootstocks. Demand for rootstocks has been high at times, with some

International research centres currently undertaking breeding programs in similar research areas, could increase collaboration, which may provide mutual benefits

less than desirable planting material (contaminated with virus and disease) used. This includes 101–14, which was widely planted and some plantings have succumbed to Cylindrocarpon root rot. While the industry has managed with the rootstocks available, there have been some issues that require more careful selection of rootstocks in the future, such as irrigated vineyards with fertile soils and high potassium levels. The spread of leaf-roll virus through infected propagation material and insect vectors is also of serious concern in New Zealand (Hoskins et al., 2011). A breeding program does not exist and industry relies heavily on nurseries for source blocks and information on performance, with little government intervention.

5.7 Summary

International research centres currently undertaking breeding programs in similar research areas, could increase collaboration, which may provide mutual benefits, (e.g. field trials in opposite hemispheres would produce two crops a year which may speed up evaluation). Advances in rapid screening techniques need to be monitored and adopted where relevant in Australia. Progress towards molecular or genetic markers is often slow or uncertain and requires long-term investment. Other international centres plant material into the field soon after laboratory evaluation, thus providing more information to growers when material is finally released. Some counties have strong control over industry, ensuring wide-spread use of certified planting material.

6. Grape Rootstock Breeding in Australia

The rootstocks available in Australia are largely those bred and selected over 100 years ago in Europe. Worldwide, the bulk of the grape industry relies on relatively few rootstock species (de Andres et al., 2007), which limits the adaptability of the grapevine across a broad range of climates and soils. The CSIRO commenced breeding rootstocks over 40 years ago and it has made a concerted effort in the past 20 years to evaluate hybrids and use that information to conduct targeted crosses to address particular issues in Australian vineyards. Research since the late 1980s focused on rootstocks with reduced potassium uptake to address high juice pH issues, combined with evaluating the rootstocks for phylloxera and nematode resistance, ease of grafting and propagation and restricting the uptake of ions, such as sodium and chloride (Wheal et al., 2002). The work now includes assessing vigour potential, WUE and the impact on wine quality.

The rootstocks available in Australia are largely those bred and selected over 100 years ago in Europe. Worldwide, the bulk of the grape industry relies on relatively few rootstock species (de Andres et al., 2007), which limits the adaptability of the grapevine across a broad range of climates and soils.

The process of developing rootstocks for lower potassium uptake commenced with the selection of 55 promising rootstocks in 1987, and the establishment of a field trial in 1989 (Ruhl, 1990a). A small number of promising selections were identified for further evaluation (Clingeleffer, 2000). Four of the rootstocks underwent evaluation for Plant Breeders Rights (PBR) purposes and testing against a wider range of phylloxera biotypes (Clingeleffer, 2007). Three rootstocks were released for industry evaluation in 2008, originally derived from crosses conducted in 1967. In Sunraysia, Shiraz grafted onto the new hybrids had lower pruning weight, yield, juice Brix and pH, higher wine colour density and total phenolics, compared with Ramsey (Clingeleffer et al., 2011a; Clingeleffer and Smith, 2011). The new rootstocks showed tolerance to some common strains of phylloxera and nematodes, but were less robust under water deficit conditions.

The most recent research project report (Clingeleffer and Smith, 2011) included several recommendations for future work. These included maintaining a germplasm of rootstock material of old and newly developed hybrids, further research on the evaluation of rootstocks, the development of rapid screening techniques and building knowledge on key rootstock traits. The general direction for grapevine breeding in Australia has been supported by industry through consultation meetings such as 'Future Rootstocks' (28 November, 2002) and 'Grapes for Growth' (1 June, 2005), along with National Rootstock Forums (2005 and 2008). There is a great opportunity for industry to be more directly engaged through an industry project reference group or similar consultative group.

The focus should be on selection, based on the predominant traits required and assessing pest resistance and other important attributes. A rootstock breeding program must have some specific endpoints and not become a never-ending program.

Producing a universal rootstock through selective breeding, including all the traits the industry may need, is unlikely in the short-term. The focus should be on selection, based on the predominant traits required and assessing pest resistance and other important attributes. A rootstock breeding program must have some specific endpoints and not become a never-ending program.

Cost benefit analysis was performed on several rootstock projects funded by GWRDC and was based around improved rootstocks from trial work and breeding (although there were other components relating to improved irrigation efficiency in some projects) (McLeod, 2001). At the time, analysis showed a relatively high return on investment of around 10:1. It would be useful to revisit the topic using known benefits and adoption rates to reassess the conclusions.

6.1 Rootstock screening

In Australia, it has taken a period of around 20 years from the beginning of screening to release the first specifically selected rootstocks based on hybrids created in 1967. These rootstocks have only been evaluated in a limited number of sites and broader commercial evaluation is required. The initial screening to measure petiole potassium concentrations of potential rootstocks was completed quickly. The subsequent field evaluation and screening for other traits was a much longer process. Similar durations from commencement of the selection process to release of rootstocks for commercial evaluation have been experienced in other countries.

Development of rapid screening methods of large numbers of hybrids for traits, including phylloxera and nematode resistance and potassium, chloride and sodium uptake, will reduce the initial selection and evaluation process and enable a quicker transition into field studies. With the use of faster screening techniques, it is anticipated the screening process would be reduced to two or three years after the initial crosses were made.

Development of rapid screening methods of large numbers of hybrids for traits, including phylloxera and nematode resistance and potassium, chloride and sodium uptake, will reduce the initial selection and evaluation process and enable a quicker transition into field studies. With the use of faster screening techniques, it is anticipated the screening process would be reduced to two or three years after the initial crosses were made. After that time, initial field testing could be undertaken for five to six years to identify the best performing selections. If PBR are to be pursued, it is suggested broader field evaluation in commercial situations could be undertaken during the period when PBR information is being collected.

6.2 Field trials

The three rootstocks selected and released through the rootstock breeding program by CSIRO were first established in a field trial in 1989. Assessments at other sites are in the early stages (first harvest 2010). Site, season and scion variety interact with rootstock performance, so it is likely different management strategies will be required to maximise performance of any particular combination. Field trials enable growers to more readily assess the performance of a rootstock under conditions similar to their own vineyard. Once a series of trials is conducted, the recommendations may not last forever as was demonstrated by ARG1 being found to be susceptible to a different biotype of phylloxera in California. In this case, there was little information available to growers on alternative rootstocks, because rootstock evaluation had ceased some years earlier (Whiting, 1996).

Trials can be at various levels to match the information required. Small replicated plots allow limited amounts of available material to be assessed and can be used to screen a range of rootstocks for site suitability. In this case, tailored vineyard management for individual rootstocks is difficult on a small number of vines. Larger scale trials can then follow with greater numbers of fewer rootstocks. Whole row treatments enable precision viticulture to be used, including yield monitors on harvesters and individual management of rootstocks. Larger trials would allow consistent vine management and may supply enough fruit for commercial size ferments, but statistical comparison is limited unless some replication is included. There are opportunities to integrate small trials with whole row or block plots by embedding the small trial within a larger block (Dry, 2005).

Field trials enable growers to more readily assess the performance of a rootstock under conditions similar to their own vineyard.

6.3 Commercialisation

Some countries use industry bodies to maintain the sanitation of rootstocks and supply 'certified' material to nurseries for subsequent bulking up and propagation (e.g. ENTAV in France, regional institutes in Germany and FPS in the USA). Generally, the adoption of new rootstocks is slow and relies on promotion by the researchers and the nurseries. For example, Gravesac (for acid soils) released in 1967 is currently the seventh most popular rootstock in France, and Fercal (for limey soils) released in 1978 is currently the fourth most popular. Adoption of a rootstock is restricted to the sites for which it is suitable, so some rootstocks will have a limit to their demand.

The CSIRO Plant Industry 'Future Rootstocks—Breeding and Strategy Plan' (revised October 2011) is based on consultation with industry, primarily in 2002. The commercialisation process proposed several key outcomes, including rapid multiplication of source blocks established on properties under test agreements, selection and licencing of nurseries to produce grafted vines for commercial sale under non-propagation agreements with PBR protection, collection of royalties and the provision of information to industry and nurseries through a variety of means. Three nurseries are currently licenced to propagate and distribute grafted vines using the three new rootstocks released in 2008.

The commercialisation model proposed by industry is similar to what occurs internationally. The main difference is that some other countries have more clearly defined groups responsible for the maintenance of the health status of candidate material (e.g. ENTAV, FPS, Geisenheim Institute). Rootstocks are then released to nurseries for the propagation of grafted vines for interested growers.

The breeding of rootstocks to suit Australian conditions commenced in 1967, with the CSIRO using introduced seeds from specified crosses in the USA. Serious consideration of rootstocks for lower potassium uptake in 1987 provided impetus for further breeding and selection. While evaluation periods in Australia have been similar to those in other countries, new procedures should speed up the process. Where the process has been quite targeted overseas, rootstocks have been released 10 years after the initial crosses were made. Developing rapid screening techniques and moving field trials into semi-commercial stages earlier will enhance the rate of commercialisation.

While evaluation periods in Australia have been similar to those in other countries, new procedures should speed up the process. Where the process has been quite targeted overseas, rootstocks have been released 10 years after the initial crosses were made. Developing rapid screening techniques and moving field trials into semi-commercial stages earlier will enhance the rate of commercialisation.

7. Industry Involvement and Feedback from Industry

Industry involvement in setting the future directions for rootstocks has occurred at several stages. Early discussions between interested groups were held on a regular basis through the Vine Improvement Research Committee, hosted by the CSIRO (e.g. Anonymous 2000). More specific consultation has occurred through a 'Future Rootstocks' meeting in November 2002, followed up by industry consultation through the 'Grapes for Growth' workshop in June 2005. The latter focused on vine genetics and concluded Australia needed to maintain an investment in vine genetics and improvement, which included breeding new rootstocks, developing markers for rapid screening and the evaluation of new varieties. Some of the more pertinent discussion points on future projects suggested there should be focus on particular issues, support for the longer term (10–15 years), targeted outcomes, use of regional sites to fast track evaluation and strong industry involvement. In addition, progress with rootstock breeding was presented at two National Rootstock Forums (2005 and 2008) sponsored by the PGIBSA. A third forum in 2011 was renamed as a 'Below the Ground' seminar sponsored jointly by the Australian Society of Viticulture and Oenology and the PGIBSA.

The Second National Rootstock Forum in 2008 produced a model for the coordination and cooperation of various groups involved in rootstocks through a Rootstock Advisory Group; however, this model has yet to gain traction. The forum also determined priorities for RD&E which were (in order) national coordination, improved information, industry standards, regional trials, rootstock improvement and rootstock physiology.

7.1 Attitudes to rootstocks

The Phylloxera and Grape Industry Board of South Australia (PGIBSA) conducted a comprehensive survey of growers and winemakers in 2000 in that state. The survey focused on their attitudes and behaviour towards rootstocks (Hathaway, 2001). At the time, PGIBSA considered (and still does) using vines grafted to phylloxera resistant rootstocks was the preferred way to deal with the threat. In 2000, around 15% of the vines in the state were grafted. The report identified the greatest barriers to planting grafted vines were the extra cost and perceived low risk of a phylloxera outbreak. While some growers recognised excess vigour and reduced wine quality as negatives for rootstock use, the majority of growers acknowledged the positive aspects and believed the negative aspects could be managed. Around one third indicated phylloxera was a reason for planting rootstocks, but two thirds indicated other reasons for planting rootstocks. More information on the choice and performance of rootstocks was identified by the survey respondents, but the author concluded better communication of existing information was also required. Since the survey, the total area of rootstocks in South Australia has increased by around 8,000-ha, taking the proportion of total plantings on rootstock to about 20%.

While some growers recognised excess vigour and reduced wine quality as negatives for rootstock use, the majority of growers acknowledged the positive aspects and believed the negative aspects could be managed.

7.2 Current industry perceptions

Twenty five wine industry personnel (Appendix B), representing a cross-section of the industry, were contacted to discuss their perceptions on current rootstock use and their needs into the future. The feedback received from industry has been pooled and condensed into six main themes (Figure 1). Note these are views of a small cross-section of the wine industry and are not necessarily the views of the author, nor should they be taken to represent the collective view of the industry because of the small sample size. Many of the views expressed were similar to the discussions recorded at the Second National Rootstock Forum in 2008 and gives a high degree of confidence that an appropriate cross-section of the industry was interviewed.

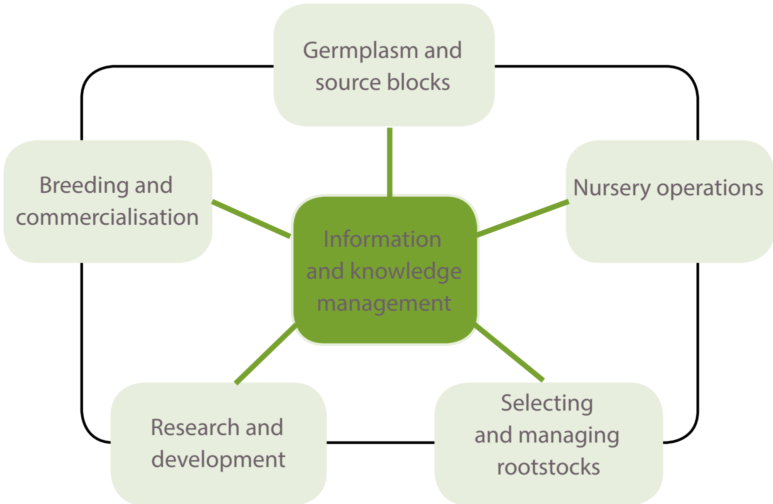

Figure 1: *Six main themes for rootstocks identified by a cross-section of the wine industry.*

Respondents took a long-term view that rootstock germplasm, while not used every year, needs to be maintained to meet new phases of grape industry planting.

7.2.1 Germplasm and source blocks

There was strong feedback about how rootstock use has changed over the years and will continue to change. Respondents took a long-term view that rootstock germplasm, while not used every year, needs to be maintained to meet new phases of grape industry planting. In the future this will primarily be replanting existing vineyards, and rootstocks are regarded as essential in most cases. Replacement of existing vineyards is ongoing to meet the needs of new consumer preferences and to replace old, under-performing vines. If all Australian vineyards were replaced after 30 years, this equates to around nine million vines required for replanting annually. Given that the majority of plantings are less than 20-years-old, the current rate of replanting is less, with rates of replanting expected to increase in the future.

The maintenance of high quality germplasm material from which multiplication blocks can be propagated, was raised by many of those consulted. The germplasm needs to be true to type, pest, virus and disease-free and maintained in such condition. A central accessible database providing relevant information was also desired by some. An Australian Grapevine Foundation Planting Scheme has been proposed (Constable and Drew, 2004) but has not been fully developed by industry, and further consideration should be given on how it may be implemented. Elite germplasm blocks are not commercial operations, as they serve to hold the repository material which is only accessed infrequently for establishing multiplication source blocks. However, their existence is vital as they form the foundation of all vineyards and their maintenance needs to be supported by industry across the board.

If all Australian vineyards were replaced after 30 years, this equates to around nine million vines required for replanting annually.

The coordination and production of planting material across the various states and agencies could be improved. The decline in new vineyard plantings has reduced the sales of cuttings. This has caused financial strain on vine improvement groups, agencies and nurseries who maintain source blocks of rootstocks, which are currently in low demand but with potential increased demand in the future (Nitschke, 2011). Some nurseries use their own rootstock source block plantings to service their ongoing requirements, and purchase additional planting material from state vine improvement groups only as required. Another issue raised by industry was the splintering of vine improvement groups through political and personal differences. The small size of the Australian grapevine industry cannot sustain a fractured approach to vine improvement and yet remain efficient. This requires strong leadership from the national industry bodies to get vine improvement working more effectively.

7.2.2 Nursery industry

The grower segment of the industry rely quite heavily on the nurseries for assistance in selecting and supplying high quality rootstocks. Most growers will pay the higher price of a grafted vine providing it is of high quality. Nurseries have had issues with viruses and diseases in grafted vines with resultant failures in the field in the past. Some viruses (e.g. stem pitting viruses) and diseases (e.g. Phaeoacromonium spp, Botryosphaeria spp, Cylindrocarpin spp, etc.) are relatively new to grapevines and infected source blocks and/or poor nursery practices have resulted in substantial issues for growers. Greater attention to germplasm and source blocks will address some of the problems. Nursery practices, such as hot water treatment, may assist with reducing some of these diseases (but not the viruses), and further research would help nurseries identify and control other sources of contamination.

A quality standard for grafted vines was also raised by interviewees, and many were disappointed with the great variation in quality of planting material during the planting boom. With a significantly lower demand, growers expect nurseries to produce consistent high quality material. There is an expectation that the Australian Grapevine Standard Scheme project will address these concerns.

Problems with incompatibility between various rootstocks and varieties or clones were regularly raised in the interviews. Individual nurseries (and growers) identified specific incompatible combinations, but there was no central registry of this information. VINA was identified as a suitable repository for this information. Little research has been undertaken to identify the causes of incompatibility and provide remedies or recommendations. The cost of grafted vines, which is an issue for some growers, relates largely to the success rate of the grafting of rootstocks and scions, and while there is a large degree of variation in graftability between rootstocks, little research is undertaken to improve the low success rate of some rootstocks. While hot water treatment has proved useful in reducing agrobacterium problems, it is not as effective against other diseases. Hot water treatment can also affect the viability of cuttings. Other nursery-related issues raised included: the lack of harmonisation of quarantine regulations between states complicating the transfer of cutting material; concern about the lack of maintenance of vine improvement source blocks; the limited availability of some rootstocks and growers having to use second rate combinations for their site.

The small size of the Australian grapevine industry cannot sustain a fractured approach to vine improvement and yet remain efficient. This requires strong leadership from the national industry bodies to get vine improvement working more effectively.

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7.2.3 Selecting and managing rootstocks in the field

Most of the interviewees were using rootstocks or had some experience with them. Of those that had little or no experience, most said they would use rootstocks for any new plantings. Around two thirds indicated that the extra cost of a grafted vine was not an issue provided they got quality vines. The predominant reasons for using rootstocks were phylloxera (control and protection), vigour control, drought tolerance, nematode tolerance, improved grape quality and salinity tolerance. Rootstocks were considered essential for replant situations, but there was some uncertainty about the performance of rootstocks in drought conditions.

There was an overwhelming response for increased regional evaluation of rootstocks, as many thought results from other regions with different soils, climate and management were unreliable. Most wanted the information to be local and in commercial scale blocks to help them decide on the rootstocks appropriate to their conditions. For combined vineyard/winery operations, there was a greater emphasis on grape and wine quality rather than yield alone. Growers were not particularly concerned about high potassium uptake or the negative impact on juice pH. This may be because there are not many penalties associated with these factors, although several winemakers indicated some rootstocks, in red varieties in particular, had caused problems.

Getting the right rootstock to match vine vigour to the site was also highlighted by many growers. In some cases high vigour was required, particularly for white grapes, where fruit exposure was not desirable (e.g. Chardonnay on Ramsey is a preferred combination in hot, irrigated areas). However, growers sought a rootstock with vigour that matches that of ungrafted vines for red varieties. A comment occasionally made by growers was a rootstock with the vigour of 101–14 or Schwarzmann was desired, but not with the high potassium uptake and low drought tolerance attributes. Other issues mentioned for more work included: rootstocks to cope with rising temperatures; stabilisation of yield and vigour fluctuations; new varieties and clones and reduction of sunburn.

The management of rootstocks was considered by many to be much improved after negative experiences early, although growers would like to see more documentation of any alternative approaches. It was also recognised that management of some rootstocks was difficult on some sites (e.g. Ramsey with red grapes in some regions), and it was better to select a rootstock that would produce less vigour. Where growers had reliable water supply, they were happy to use Schwarzmann, but Schwarzmann suffered badly in droughted areas where irrigation was limited. Most used irrigation to manipulate vigour and many just managed grafted blocks according to vine growth. The general process for rootstock selection was to look at the market requirements and determine variety and clone, then consider their site attributes (soil, climate, salinity, pests and disease, risk of issues developing) to determine a range of potential rootstocks, and then approach nurseries to ascertain availability and quality of material available. Growers often mentioned that their selection was compromised due to their optimum scion/rootstock combinations not being available.

The predominant reasons for using rootstocks were phylloxera (control and protection), vigour control, drought tolerance, nematode tolerance, improved grape quality and salinity tolerance.

7.2.4 Research and development aspects

A predominant view of the interviewees was that there were sufficient rootstocks in Australia and there was a need for more thorough evaluation of these rootstocks. Growers tended to concentrate on their own situation and think in the short-term (i.e. what are the issues affecting them now and into the immediate future). Hence, many think about selection of currently available rootstocks suited to their current conditions and do not consider future conditions and suitable characteristics. Across all those interviewed, around two thirds of the growers using rootstocks indicated they had issues with the rootstocks they were using, and on aggregating individual information, it was apparent there were deficiencies with all rootstocks.

Most wanted the information to be local and in commercial scale blocks to help them decide on the rootstocks appropriate to their conditions.

As mentioned earlier, respondents wanted to see more regional testing of rootstocks to provide information pertinent to their local conditions. Longevity of grafted vines was raised a few times, and it was proposed that some of the older rootstock trials established 30–40 years ago may be available for reassessment. Also, the issue of how many regional situations are needed to cover likely soil/climate variations when evaluating rootstocks was raised, as well as consideration to re-examining results from all available trials to see if some benchmark sites can be identified. For example, an earlier GWRDC-funded project on soils and rootstock trials (Cass et al., 2002) contained rootstock performance and soil data available for analysis, which was not fully undertaken at the time. Climate data could also be integrated into such an analysis. Greater collaboration with overseas colleagues was also mooted as a way of advancing our understanding of rootstocks.

Interviewees provided feedback on where they thought there were gaps in the information available, and the more commonly raised points included rootstock issues related to incompatibilities, uneven growth between wet and dry years, rising temperatures, excess vigour, drought tolerance, inconsistent grape and wine quality, phylloxera biotypes, aggressive nematode strains, salinity, producing 'fine' wines, colour stability, high potassium and juice pH, cooler and wetter regions, improving phosphorous uptake, better utilisation of nitrogen, drought predisposing vines to pests and disease and scion to rootstock signals.

7.2.5 Breeding and commercialisation of rootstocks

A predominant view of the interviewees was that there were sufficient rootstocks in Australia and there was a need for more thorough evaluation of these rootstocks.

Around half of the interviewees had taken some degree of interest in rootstock breeding and supported the CSIRO program. However, they were concerned about the slow pace of evaluating and releasing rootstocks and identified a perceived gap between the amount of funds invested and the outputs. The CSIRO have been following a 'Breeding and Strategy Plan' developed from an industry meeting in November 2002. The plan considered the market for rootstocks, breeding objectives, breeding vs importing, breeding strategies, intellectual property and the commercialisation plan. Commercialisation primarily involves obtaining PBR protection on promising rootstocks, establishing multiplication blocks, selecting and licencing nurseries, purchasers signing non-propagation/distribution agreements and royalties going back to investors (CSIRO, GWRDC and HAL) to contribute to ongoing research.

A number of production-related issues have been described in the earlier sections of this report, towards which breeding may provide answers. These issues are principally the ones outlined in the 'Breeding and Strategy Plan', but tolerance to heat and rootstocks for cooler and wetter regions were also mentioned by interviewees. Of interest to the interviewees would be the development of more rapid screening techniques which would speed up the selection process. Some interviewees questioned the lack of independent evaluation of potential new rootstocks. They cited it was a constraint to adoption, since the perception was that plant breeding organisations, in general, have a self-interest in promoting their own products. Opportunities to import rootstock material should also be considered.

7.2.6 Information and knowledge management

Many of the interviewees indicated there was plenty of information available, but it was either not readily available or not presented in the right context to encourage the adoption of rootstocks. Some indicated the information was hard to keep up with and there were mixed messages about some rootstocks. For example, different tests had been used to determine drought tolerance and results varied between the tests and field experience. The terminology surrounding drought tolerance and WUE also needs further explanation.

Many of the interviewees indicated there was plenty of information available, but it was either not readily available or not presented in the right context to encourage the adoption of rootstocks.

There was a general belief that there will be another growth phase and interviewees wanted to be prepared. The most common sources of information were publications, local trials (where available), Yalumba nursery website, discussion with nurseries, general internet searches, consultants, PGIBSA rootstock book (Dry, 2007) and other growers. With the latter, there can be a disconnect between what the growers want (yield) and what the wineries want (quality). There were several mentions of updating the PGIBSA book, which is focused on South Australian regions, and expanding it to include other Australia wine regions. An individual grower may only need to refer to information on rootstocks for a short period when making a decision on rootstock selection and may not need information until replanting 20–30 years later. However, replanting is likely to be spread over many years to minimise fluctuations in income while blocks are out of production.

A few of the interviewees indicated there is resistance to the adoption of rootstocks from some winemakers (mainly related to excess vigour and poor grape quality), and some growers who do not see any particular benefit in a rootstock (e.g. in the MIA water supply is assured and salinity is not an issue). Continuation of the (currently) triennial rootstock forums was also seen as essential and that the PGIBSA is the appropriate lead agency for that event.

The growers interviewed generally fitted into one of five groups. The groups were those that:

1. did not need rootstocks
2. did not have rootstocks but would consider rootstock use in the future
3. had some rootstocks and would consider planting again in the future
4. needed rootstocks for replant situations in all future plantings
5. always required rootstocks due to existing issues.

It is likely each group will have different information needs and this should be considered in any extension activities.

Attention to all six themes will be required for the efficient development of the wine industry. If there is insufficient or no progress in one or more of these themes, the full potential for rootstock use within the wine industry will be inhibited. The industry seeks good quality planting material, rootstocks suited to their site, a breeding and selection program that can address any deficiencies in the current rootstocks and improved access to information presented in a context suited to their needs. Growers and winemakers know there may be unknown issues in the future and that the industry must be ready to adapt. Rootstocks will be part of that adaption process.

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8. Conclusions

The present use of rootstocks in Australia is relatively low compared with most other countries. Historically, there has not been a great need to use rootstocks, due to many new areas being planted on previously unplanted soil, and the absence of soil pests and diseases from many wine growing areas. Recent drought conditions have encouraged the industry to consider rootstocks and many replant situations required rootstocks to overcome nematodes. Current economic conditions in the industry preclude wide-spread replanting but replacement replanting will be required over the next 10 or more years. As replanting increases, industry needs to be ready with an appropriate selection of rootstocks with high quality, healthy planting material. Industry also needs to be in a position to respond to a critical need for rootstocks if that arises (e.g. new phylloxera outbreaks).

Techniques developed in breeding programs to understand the genetic basis of traits, and the development of associated rapid screening techniques, have beneficial application for the current suite of rootstocks, also. Any new rootstocks need to have points of difference from the existing range and need to instil a competitive advantage in the market place. The three recently released CSIRO rootstocks appear to fulfil this requirement. The information required by growers and nurseries are variable, with only those seriously considering planting on rootstocks actively seeking information. The industry would suffer in the longer-term if R&D on rootstocks did not continue.

A number of factors influence the use of rootstocks by the wine grape industry, and market failure in any one of these areas would lead to a reduction in competitive advantage or industry resilience. Some of these facets may not require significant investment from GWRDC, but may require GWRDC's input into facilitating progress and working with other grape industry bodies. Under present circumstances, the rate of rootstock planting is slow. However, there has been strong interest in replanting with rootstocks, as some existing vines need replanting due to their condition, change in market demand or poor adaptation to their current site. Most in the industry were optimistic about the future and would focus on replanting once profitability returned. While there is a lull in vineyard redevelopment and planting, now is an opportune time to ensure the industry has suitable infrastructure and systems for rootstocks in the future.

Future investment in rootstocks in Australia for evaluation, breeding and commercialisation should be directed toward the following:

8.1.0 Evaluation of rootstocks

8.1.1

A high standard of cleanliness of elite planting material needs to be maintained from which multiplication source blocks can be established as required. This necessitates regular virus and disease testing and maintenance, the cost of which should be borne across the grape industry, so there are opportunities for co-investment. Practical techniques need to be investigated and implemented to reduce or prevent the infection of source blocks. There are issues about where such plantings should be located. The various vine improvement groups need to work closely with each other and with industry, and the GWRDC may play a facilitation role with other industry bodies to improve the functioning of the system. Industry feedback noted this as a high priority issue.

Recent drought conditions have encouraged the industry to consider rootstocks and many replant situations required rootstocks to overcome nematodes. Current economic conditions in the industry preclude wide-spread replanting but replacement replanting will be required over the next 10 or more years. As replanting increases, industry needs to be ready with an appropriate selection of rootstocks with high quality, healthy planting material. Industry also needs to be in a position to respond to a critical need for rootstocks if that arises (e.g. new phylloxera outbreaks).

8.1.2

Producing high quality planting material through nurseries is an integral part of the wine industry. Industry feedback indicated the need for high quality planting material free of diseases and incompatibility issues. Some funds need to be allocated to ensure this occurs, preferably as co-investment with the nursery industry. Some independent, random sampling of nursery material may be necessary to ascertain the extent of the problem. The nursery costs arising from incompatibilities, disease in multiplication blocks, poor nursery hygiene and poor graftability, get passed on to the buyers and there is an opportunity to reduce the cost of planting material—one of the barriers to the use of rootstocks. Research into incompatibilities, diseases in propagation material and improving graftability of some scion/rootstock combinations is warranted.

8.1.3

There is very strong interest from industry in drought tolerance and improved WUE, which are not necessarily the same thing. However, there needs to be a clearer understanding of the differences between the two by industry, along with what criteria should be used to determine appropriate rootstocks for particular situations. The current GWRDC project CSP 09/01 is addressing these issues. It needs a firm focus on tools that can be used to rapidly assess drought tolerance and WUE that can be translated into screening existing rootstocks, so industry has some firm guidelines to go on with. While the mechanisms for WUE are reasonably well understood, it appears premature to conduct breeding and selection for drought tolerance until the key underlying traits are determined and screening tools developed. A comprehensive review of drought tolerance mechanisms may provide clearer direction for progress on this issue.

8.1.4

The location and duration of field testing of rootstocks was an issue mainly raised by the researchers. There is an expansive range of rootstock trials in the country that have been analysed individually, but not across the board. The broad-acre cropping industry has used its extensive range of breeding evaluation sites to refine the number of locations they need. It would be worth engaging some biometric expertise to firstly determine the feasibility of analysing the range of rootstocks trial data available along with an analysis of soil (GWRDC project CRS 95/1) and climate data. And secondly, to conduct an analysis to determine such things as optimum length of time of data collection, the influence of soil and climate characteristics, trial design and the feasibility of determining benchmark sites to which most growers can relate. At the least, there needs to be some basic soil, climate and water availability information that growers need to collect that can be matched to an appropriate rootstock selection.

8.1.5

Most growers said they wanted to see how rootstocks performed locally to be more confident in making a choice. A first step would be to collate and analyse the current performance of rootstocks in a region (for example: Wigg, 2006) with GWRDC support. Such a summary may identify some significant gaps in knowledge which could be further explored through trials or block plantings. Not many growers initiate their own experimentation, but they are happy to participate in trials if offered to them. GWRDC may be able to facilitate a package where small trials are propagated through a cooperating nursery and are offered to regional groups pending co-investment. Small plots using Latin square single vine plots were effectively used in Sunraysia for the initial evaluation of nematode rootstocks.

Any new rootstocks need to have points of difference from the existing range and need to instil a competitive advantage in the market place.

8.1.6

The Phylloxera and Grape Industry Board of South Australia publication on 'Grapevine Rootstocks' (Dry, 2007) was well recognised as a good source of information. Those in other states commented that it would be good to have such a book on a national basis, particularly providing recommendations for all regions. Consideration should be given to printing a similar publication, or adapting it to the internet, in conjunction with the PGIBSA and other grape industry bodies.

8.2 Rootstock breeding

8.2.1

The CSIRO Plant Industries 'Breeding and Strategy Plan' was based around an industry consultation meeting in 2002. It is timely to revisit the plan and check whether the intervening period has changed industry perceptions of breeding rootstocks and the commercialisation process. A number of lessons have been learnt during the process of releasing the first batch of rootstocks and the process needs reviewing. While the National Rootstock Forums provide an overview of the program, industry and CSIRO would benefit from more regular and closer review of the breeding and commercialisation program.

The industry would suffer in the longer-term if R&D on rootstocks did not continue.

8.2.2

Useful rapid screening approaches have been developed for some issues relating to rootstock performance (e.g. nematodes, phylloxera, potassium, sodium and chloride). The capability to undertake screening needs to be maintained (e.g. screening current and emerging rootstocks against virulent nematodes that emerge), and expanded to other attributes required of rootstocks, such as phosphorous and nitrogen uptake.

8.2.3

Under present circumstances, the rate of rootstock planting is slow. However, there has been strong interest in replanting with rootstocks, as some existing vines need replanting due to their condition, change in market demand or poor adaptation to their current site.

Breeding for traits that provide the Australian industry with a competitive advantage should continue. The largest part of the industry produces quality wine with low production costs, so this is one area to focus on. Those producing premium wines are looking more for consistency of vine growth and quality in a variable climate.

8.2.4

Collaboration with overseas breeding institutes should continue and be strengthened to cooperatively develop genetic, biochemical, physiological and molecular markers. The process is quite involved and greater progress could be made by sharing resources. This may involve segregation of the work on the development phase and cooperation on the evaluation phase. This is higher risk research, as evidenced by inconclusive results for developing markers for resistance to root-knot nematode (Cousins pers. comm.). Some promising results appear to be coming out of the salinity research and it would be valuable to see that through and evaluate its usefulness in screening rootstocks.

8.2.5

An aspect of evaluating new rootstock hybrids that does take time is the field assessment. Industry should look at ways of speeding up the process of assessment by rapid propagation techniques, earlier establishment of the initial field trial, quicker transition to regional evaluation and the use of semi-commercial evaluation, as done with new V. vinifera cultivars.

While there is a lull in vineyard redevelopment and planting, now is an opportune time to ensure the industry has suitable infrastructure and systems for rootstocks in the future.

8.2.6

Most breeding programs in the past have had timeframes of around 20 years to commercial release, but this period should be able to be reduced to around 10–15 years. Projects could be funded in five year periods—with the breeding, screening and selection occurring in the first period, initial field evaluation and preparation for semi-commercial release in the second period, and broader field evaluation and monitoring in the third period. If projects don't meet the targets at the end of anyperiod, then they can be halted at that stage.

8.3 Commercialisation

8.3.1

Since GWRDC has an investment in new rootstocks, it is in its interest to ensure the commercialisation process is expedited. There are issues with quarantine regulation between states, including the treatment of planting material that diminish the viability of cuttings and grafted vines. Some investment in these aspects, and points raised in 8.1 above, is warranted to ensure sales of new rootstocks are not compromised.

8.3.2

Growers and winemakers often do not make decisions based just on published information, but they like to observe the vines performing in the field and see and taste the wines from different treatments. There are opportunities to use this process with the current field plots with the new CSIRO rootstocks. Such activities could be funded through regional viticulture technical groups, state extension officers, wine company Grower Liaison Officers and Industry Development Officers. Funds may be required to assist with small scale winemaking if commercial wines are not available.

8.3.3

There is a need to continue the provision of information in a range of formats. While the availability of the new CSIRO rootstocks has been mentioned in industry publications for several years, many growers interviewed were not aware of them—primarily because they were not in the process of planting on rootstock and had no need for that information. When they decide to plant with rootstocks is when the information will attract their attention. Growers tend to consult the nurseries as a major source of information, so the information needs of nurseries need to be addressed . Consideration should also be given to formulating information so it appears readily on internet searches, perhaps with a regional focus. For example, the grains industry provides the results of variety trials on the internet using an interactive map (see www.nvtonline.com.au). Other means, such as applications for smart phones, should also be considered. In the event of a rapid increase in interest in rootstocks due to a critical situation (e.g. a new phylloxera outbreak), information should be ready to go into targeted packages. Since it is difficult to predict what situation might stimulate a sudden increase in rootstock planting, it is difficult to justify preparing information packages in advance.

Growers tend to consult the nurseries as a major source of information, so the information needs of nurseries need to be addressed .

9. Recommendations for GWRDC Action

The main issues facing the wine grape industry, with regard to rootstocks, are:

1. maintaining rootstock (and scion) source vines as 'high health status' and ensuring that the status is maintained through to the purchaser of the planting material
2. ensuring relevant field evaluation information is available to assist in the selection of rootstocks for vineyard plantings
3. developing rapid screening techniques to select rootstocks with appropriate characteristics and, where gaps are identified, undertake introductions or targeted breeding to address those gaps.

A number of activities may be funded by GWRDC alone or in partnership with other grape and nursery industry organisations, or the GWRDC may act as a facilitator to ensure appropriate outcomes are met. The following recommendations address the key issues identified in the review.

1. Nuclear germplasm material, from which multiplication blocks are derived, need to be monitored and maintained in a true to type and high health status. This activity is not a commercial proposition due to the need to maintain infrequently used material. Industry needs to support it financially, whether that be through GWRDC and other grape and nursery bodies, or a funding model to be determined. The establishment of an Australian Grapevine Foundation Planting Scheme was proposed in 2004 and GWRDC should pursue the establishment of this group. The downstream use of planting material through multiplication blocks and nurseries should also be monitored to maintain the high health status through to customers. GWRDC and other grape industries need to co-invest with vine improvement bodies and nurseries to address issues related to maintaining high health status planting material to the industry.
2. An assessment of the potential to extract improved guidelines for the selection of rootstocks for field plantings, should be initiated using available trial information—largely based on the work on soils and rootstocks conducted by Cass et al. (2002)— also including climatological and other relevant information. If the above appears feasible, analysis of the data should be conducted with the aim to provide better and easily measurable guidelines for industry on the selection of rootstocks for their particular site. At the very least, rootstock trial data could be made more accessible on the internet through an interactive map, as the grains industry has done. GWRDC should also support a process whereby regional groups can review the performance of rootstocks locally (such as in the Ovens Valley, Wigg, 2006). If significant gaps are identified, GWRDC would facilitate the implementation of local trials. Given the importance of wine quality to the industry, GWRDC should provide funding to assist the making of wines from new rootstocks for demonstration purposes to growers and winemakers.
3. Funding support for the strategic introduction of rootstocks for public benefit should be considered, in conjunction with other beneficiaries. Rapid screening techniques should continue to be developed with the support of GWRDC, and other grape industry groups, to assess current and prospective rootstocks, initially with a focus on drought tolerance and WUE in conjunction with GWRDC project CSP 0901. Where there are gaps in the ability of current rootstocks to address particular issues, or where a particular market advantage can be identified, breeding and selection for targeted outcomes should be supported. Inherent in such a project is the need to:

- establish and have regular contact with an industry consultation group for grapevine breeding
- have an industry consultative group conduct a review of the 'Future Rootstocks – Breeding and Strategy Plan', developed with industry in 2002
- develop a staged process for rootstock breeding and evaluation, broadly encompassing a breeding and screening stage, an initial field evaluation stage and a broader field evaluation/ semi-commercialisation phase, with a comprehensive review against outcomes before proceeding to a subsequent stage
- develop rapid field evaluation procedures to speed up the process
- continue with and broaden contacts with potential collaborators.

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Appendix A

GWRDC Rootstock Review —Terms of Reference

Overview:

GWRDC is currently reviewing its investment into rootstock breeding and other associated rootstock research and development (the Review). The Review will summarise relevant literature and document the current state of play and the major gaps in research and development for wine-related viticulture. The Review will be conducted with a view to guiding GWRDC's future investments in this area. GWRDC is seeking recommendations on where the most effective future investments can be made to add value to the considerable body of rootstock-related research and development already in the public and commercial domain. The Review will evaluate the current CSIRO Plant Industry rootstock breeding program, briefly document activities and progress in other international grapevine rootstock breeding programs and provide recommendations to GWRDC on the usefulness to the Australian wine sector of future investments.

Consultation with:

1. a cross-section of industry representatives (nursery operators, growers, consultants, Phylloxera and Grape Industry Board of South Australia [PGIBSA], grower liaison officers, winemakers and marketers—a minimum of 20 selected in consultation with GWRDC), to better understand what industry demand there is for new and existing rootstock varieties in Australia, and what information gaps exist in relation to the use and management of the current suite of rootstocks available both in Australian and overseas.
2. the research community, both domestically and internationally (10 Australian and at least five international representatives), about the current status of active rootstock breeding programs internationally, that focuses particularly on those rootstock breeding programs linked to improving the performance of wine-related outcomes. This should include investigating the timelines from initiation to commercialisation of particular rootstock selections, the resourcing input levels and the commercialisation models used within industry.

Consideration of:

1. viticulture-related rootstock research and development funded by GWRDC and other international research and development partners, including but not limited to Prof. Andrew Walker, UC Davis, CA; Dr Peter Cousins, USDA, Geneva, NY, and Dr Ernst Ruhl, Geisenheim Research Institute, Germany.
2. GWRDC's initiated review—May, P., (1994), Using Grapevine Rootstocks - The Australian Perspective. Grape and Wine Research Corporation, Adelaide.
3. PGIBSA coordinated rootstock forums and the outcomes of the meetings held in Mildura in 2005 and 2008.
4. Dry, N., (2007), Grapevine Rootstocks: Selection and Management for South Australian Vineyards, Lythrum Press in association with Phylloxera and Grape Industry Board of South Australia.

Expectation to:

1. work with GWRDC staff with respect to methodology, external participants and project outputs.

2. conduct one-on-one interviews that will engage the key scientific and industry representatives actively working on in the area of rootstocks within viticulture both in Australia and internationally.

3. review relevant project reports, scientific literature and reviews conducted within the broader viticultural sector (wine, dried and table grape).

4. make recommendations to GWRDC on future research in relation to the management of existing rootstocks and the need/demand for a rootstock breeding program within Australia.

5. identify, prioritise and detail areas for future research in relation to the breeding, evaluation, commercialisation and management of rootstocks in the Australian wine sector.

Deliverable:

A report on the priorities identified by the Australian wine industry representatives and the national and international research representatives that includes:

1. an evaluation on the relevance and significance of the current CSIRO Plant Industry rootstock breeding program in relation to other international grapevine breeding programs.

2. an assessment on the Australian wine sector access to outputs from the current rootstock breeding program.

3. recommendations on the most effective future investment for GWRDC in relation to breeding, evaluation and commercialisation of rootstocks for use in the Australian wine sector (Report).

Appendix B

Guidelines for Industry Interviews and People Interviewed

Guidelines for Industry Interviews

1. Do you currently use rootstocks or see a need for rootstocks? If not, why not?
2. In your vineyard/region what are the reasons you currently require rootstocks? (Phylloxera, nematodes, drought, salinity, vigour management.)
3. Where have you obtained information from to determine what rootstock to use? (Consultants, books, industry journals, field days, internet, Yalumba website, R&D reports, government agencies, soil tests.)
4. What things do you consider when selecting a rootstock and do you rate them high, medium or low importance? (Yield, vigour, berry size, wine quality, longevity, environmental impact, juice pH, grape colour, royalties, compatibility, cost, nursery quality.)
5. Do you think that rootstocks need to be managed differently to ungrafted vines and what sort of things do you do differently? (Nutrition, trellis, canopy management, irrigation, P&D control.)
6. Have the rootstocks used in your vineyard/region changed over the years? Why? (New information, local trials, new issues developed in vineyard, more drought conditions, better material available, winemakers wanted something different.)
7. Thinking about the future, do you think the current rootstocks that are available will be adequate for your future needs? Why? (Climate change, new P&Ds might appear, increasing salinity in region.)
8. What are the shortcomings with the current rootstocks? (Too vigorous, too costly, my site conditions are extreme, not drought tolerant.)
9. What needs to happen to address any shortcomings in current rootstocks? (More basic R&D, more applied R&D, more imports from overseas, better transfer of information we already have, more field demonstrations, case studies, more local breeding.)
10. Can we rely on overseas countries to provide the rootstocks we need? Why?
11. Do you follow what's happening with breeding rootstocks in Australia? Why?
12. What process would you go through that results in you changing rootstocks? (A rootstock fails, identify a need, collect information, consult others, trial different ones on my vineyard, final decision.) What are the most difficult stages?
13. What are the priority areas for the future of rootstocks in Australia?
14. Any other comments on where the Australian industry should be heading in regard to the breeding, use and evaluation of rootstocks?

List of Industry People Interviewed

John Beresford, Mitchelton Wines, Nagambie, Victoria

Malcolm Campbell, Campbells Wines, Rutherglen, Victoria

Jim Campbell-Clause, AHA Viticulture, Western Australia

Brian Currie, Westend Estate, Griffith, New South Wales

Paul Dahlenburg, Treasury Wines, Glenrowan, Victoria

Nick Dry, Yalumba Nursery, Nuriootpa, South Australia

Andy Gordon, KC Vine Nursery, Trentham Cliffs, New South Wales

Paul Greblo, Sandhurst Ridge Wines, Marong, Victoria

Russell Johnstone, Consultant, McLaren Vale, South Australia

Stephen Lowe, Stony Creek Vineyard, Edi Upper, Victoria

Kym Ludvigsen, Fox Hat Vineyard, Ararat, Victoria; Chair, Australian Vine Improvement Association

Geoff McCorkelle, McWilliams Wines, Griffith, New South Wales

Bret McLenn, Brown Brothers Wines, Milawa, Victoria

Jeff Milne, Zilzie Wines, Karadoc, Victoria

John Monteath, Balgownie Estate, Maiden Gully, Victoria

Alan Nankivell, Phylloxera and Grape Industry Board of South Australia

David Oag, Department of Employment, Economic Development and Innovation, Queensland

Stephen Partridge, Agribusiness Research and Management, Busselton, Western Australia

Ken Pollock, Blackjack Wines, Harcourt, Victoria

Liz Riley, Vitibit, Hunter Valley, New South Wales

Nathan Scarlet, Rathbone Wine Group, Port Melbourne, Victoria

Liz Singh, Murray Valley Wine Growers, Mildura, Victoria

Tim Smythe, Riverland Winegrape Growers Association, Loxton, South Australia

Mark Walpole, Aquila Audax Enterprises, Whorouly South

Paul Wright, Vinewright, Mt Pleasant, South Australia, Chairman, Vine Industry Nursery Association

Appendix C

List of Scientists and Others Contacted

Mr Peter Clingeleffer, CSIRO Plant Industry, Adelaide, South Australia

Dr Marissa Collins, CSIRO Plant Industry, Adelaide, South Australia

Dr Peter Cousins, USDA, Geneva, New York, United States of America

Mr Andrew Downs, PGIBSA, Adelaide, South Australia

Assoc Prof Peter Dry, AWRI, Adelaide, South Australia,

Dr Greg Dunn, NWGIC, Wagga Wagga, New South Wales

Prof Jim Hardie, CSU, Wagga Wagga, New South Wales

Dr Markus Keller, Washington State University, Prosser, Western Australia

Dr Michael McCarthy, SARDI, Nuriootpa, South Australia

Dr Nathalie Ollat, INRA, Bordeaux. France

Dr Kevin Powell, DPI Victoria

Prof Dr Ernst Ruhl, Forschungsanstalt Geisenheim, Germany

Dr Brady Smith, CSIRO Plant Industry, Adelaide, South Australia

Dr Rob Stevens, SARDI, Adelaide, South Australia

Dr Mike Trought, Marlborough Wine Research Centre, Blenheim, New Zealand

Prof Andrew Walker, University of California, Davis, California

Dr Rob Walker, CSIRO Plant Industry, Adelaide, South Australia